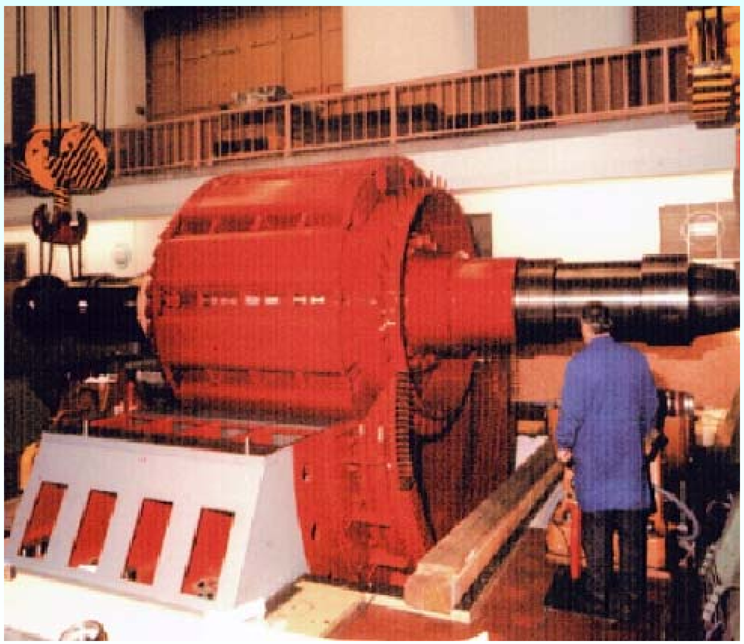
Grossgeneratoren und Hochleistungsantriebe
Large Generators and High Power Drives

Lectures SS 2+1

Prof. Dr.-Ing. habil. Andreas Binder

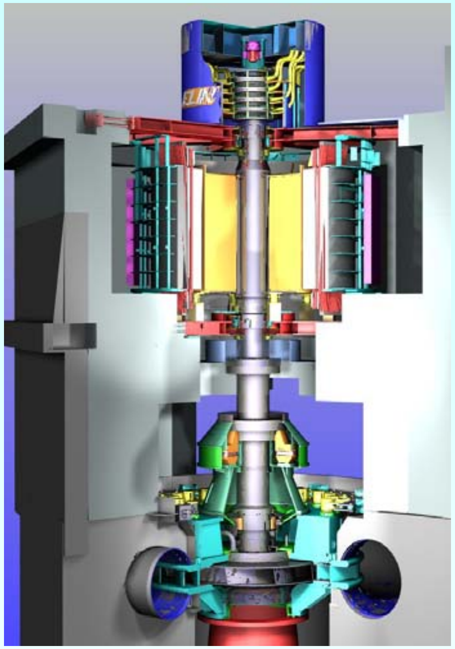


Large Generators and High Power Drives

Contents of lectures

1. Manufacturing of Large Electrical Machines
2. Heating and cooling of electrical machines
3. Eddy current losses in winding systems
4. Excitation of synchronous machines
5. Design of large synchronous machines
6. Wind generators and high power drives
7. Forces in big synchronous machines

Grossgeneratoren und Hochleistungsantriebe
Large generators and High Power Drives



Vorlesung SS 2+1

Prof. Dr.-Ing. habil. Andreas Binder

Inhalt der Vorlesung

- 1. Der Weg zum modernen Elektromaschinenbau
  Von den Anfängen zum „state-of-the-art“ - Ausblick
- 2. Hochleistungskühlung:
  Hohlleiterkühlung, Wasserstoff- und Wasserkühlung, Topair-Luftkühlung
- 3. Wirkungsgradoptimierung:
  Wirbelstromverluste verlustarme Maschinenbemessung, Sonder-werkstoffe, Zusatzverluste bei Umrichterspeisung
- 4. Erregerbedarf von Synchronmaschinen
  Erregersysteme, Ermittlung des Erregerbedarfs

Grossgeneratoren und Hochleistungsantriebe
Large generators and High Power Drives

- 5. Große Synchronmaschinen elektrische Energie-erzeugung: Turbogeneratoren für thermische Kraftwerke, Schenkelpolgeneratoren für Hydro-Kraftwerke
- 6. Windgeneratoren und Hochleistungsantriebe: Doppeltgespeiste und getriebelose Windgeneratoren, Stromrichter-motoren und große Permanentmagnetmaschinen (Schiffsantriebe, Verdichter, Rohrmühlen, Drehöfen, Großgebläse)
- 7. Kräfte und Schwingungsanregungen: Elektrodynamische Parasitärkräfte, Vibrations- und Geräuschanregung, einseitiger magnetischer Zug, Kurzschlußkräfte und Gegenmaßnahmen

Übung

Ausführliches Skript: für Vorlesung und Übungen

Exkursion

1. Manufacturing of Large Electrical Machines

- History and significance of electric machinery

- State-of-the art of medium and high power machines

- Trends in large generators and high power drives

1. 1. History and significance of electric machinery

-First electric machines in the second half of the 19th century. Main focus on DC machines and permanent magnet excitation.

1866: Discovery of self-excitation of shunt-wound DC generators, based on iron remanence ("dynamoelektrisches Prinzips“) by *Werner v. Siemens, Germany*

$\rightarrow$ Strong development of DC-machines: 1881 Int. Ele. Exhibition, *Paris*!

1885: *Prof. Ferraris (Torino, Italy)* describes rotating magnetic field principle

$\rightarrow$ Strong development of AC synchronous and induction machines

1888: First cage induction machines, *Michael v. Dolivo-Dobrowolsky, AEG, Berlin, Germany*

1901: First cylindrical rotor synchronous machines, *Charles E. Brown, Brown-Boveri-Company, Mannheim, Germany*

$\rightarrow$ strong development of high speed AC synchronous generators for steam turbine operation

1912: Invention of twisting of cooper strands to reduce AC eddy current losses in copper conductors, *Ludwig Roebel, BBC, Mannheim, Germany*

1. 1. History and significance of electric machinery

-First electric transformers:

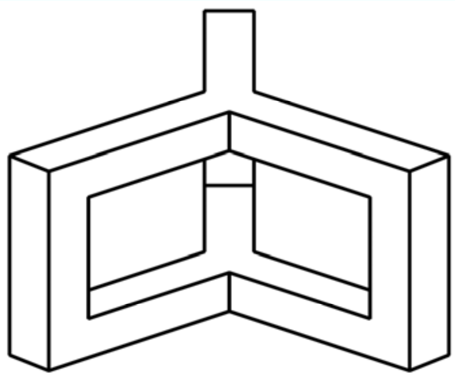
1830: Discovery of law of induction by *Michael Faraday*, *London, England*

1856: *S. Varley, England,* constructs a transformer with a closed iron core

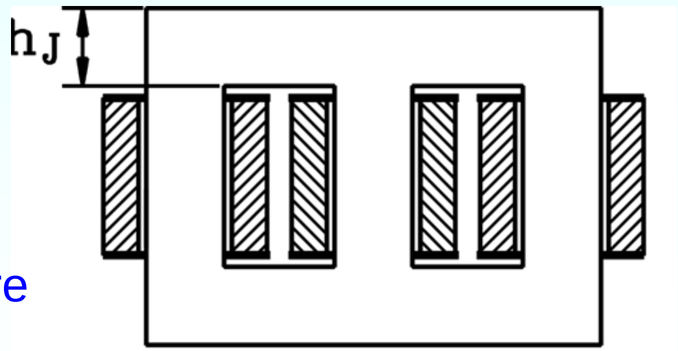
1881: *Blathy, Deri* and *Zipernovsky* build at the *Ganz* factories, *Budapest*, *Austrian-Hungarian Empire*, the first modern single phase transformer with iron core and separated low and high voltage winding

1889-1891: *Michael v. Dolivo-Dobrovolsky* constructs and builds the first three-phase transformer with the modern three-leg iron core instead of the older temple construction, at *AEG. Berlin, Germany*

Temple type: Magnetically symmetric iron-core for 3-phase transformers



Dobrovolsky´s **Three-leg type**: Magnetically asymmetric, but cheaper iron-core for 3-phase transformers



1. 1. History and significance of electric machinery

Proof of **economically feasible transport of high power electric energy:**

1886 DC-line with a power of 30 kW, 2500 V via 8 km from *Kriegstetten* to *Solothurn, Switzerland,* manufactured by *Maschinenfabrik Oerlikon*

1891 Three-phase AC transmission of an apparent power of 210 kVA via 175 km from *Lauffen/Neckar* to *Frankfurt/Main, Germany (Ch. Brown, M. v. Dolivo-Dobrowolsky)*

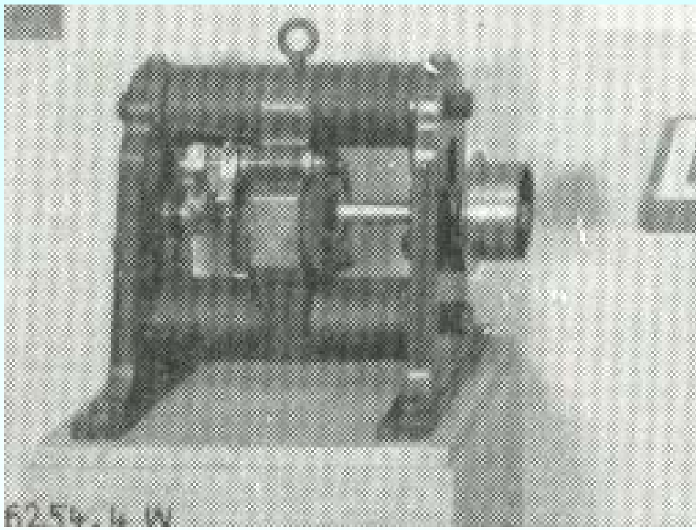
-Advantages of AC transmission by high voltage and power transformers clearly understood.

- End of the quarrel between DC and AC protagonists (DC: *Th. A. Edison*, AC: *N. Tesla*) in favor of AC transmission

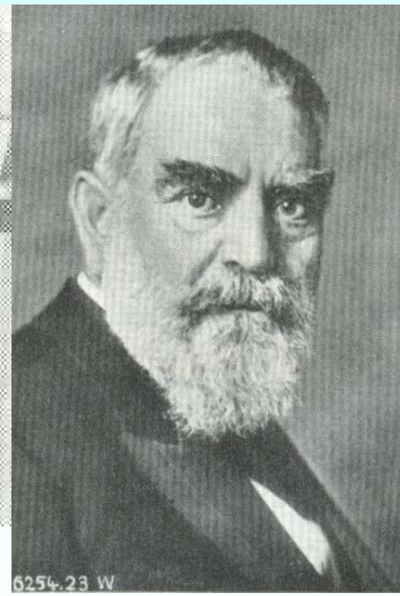
- With the advent of the power thyristor in 1955 the high voltage DC transmission becomes a interesting alternative (HV DC). Only real power is transmitted, no travelling waves, no capacitive AC loading current. Pioneers e.g. *Robert Joetten, TU Darmstadt* (1970-ties).

1. 1. History and significance of electric machinery

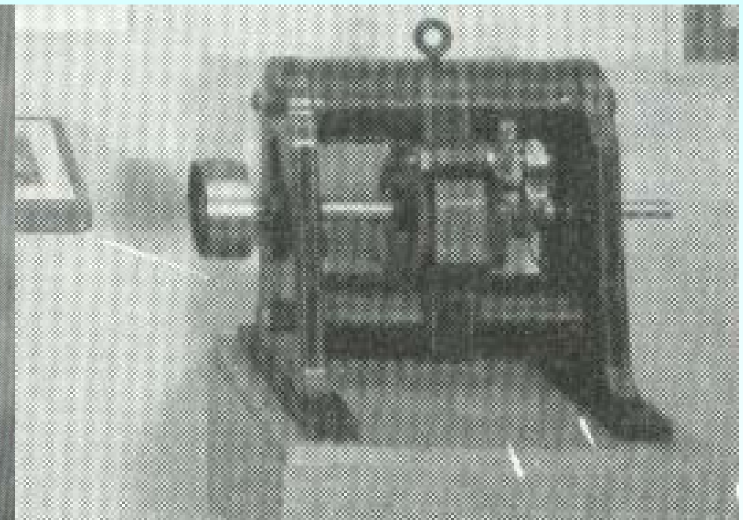
1882: *M. Deprez*: First DC electrical power transmission: From *Miesbach* to *Munich* via 57 km a power of ca. 1000 W, 2000 V was transmitted, based on an idea of *Oskar v. Miller*



Two-pole DC Generator

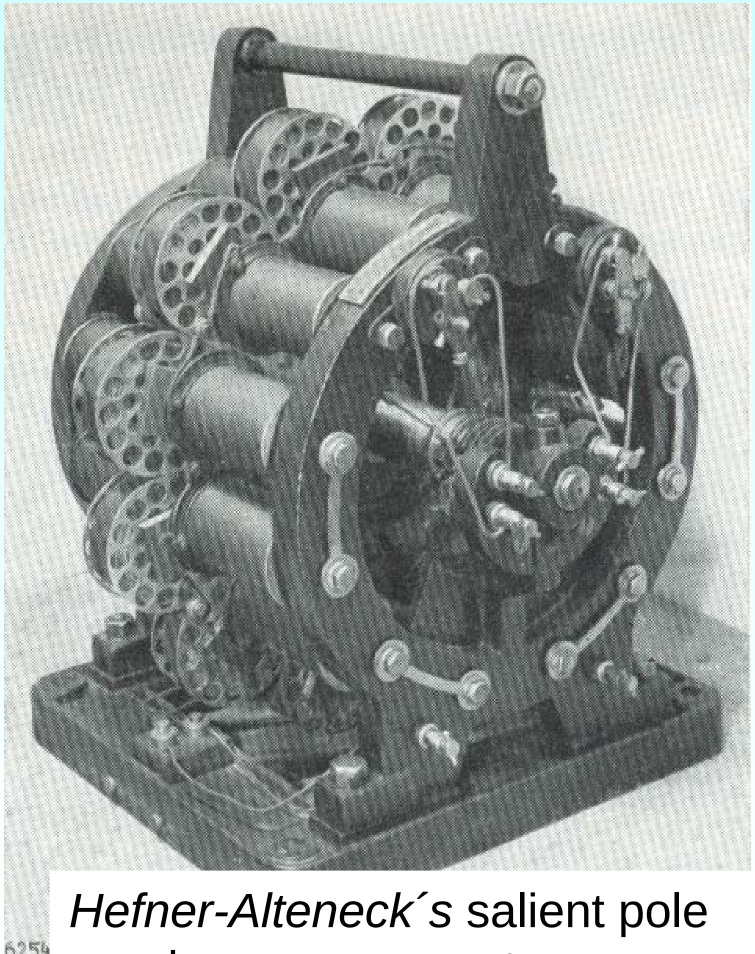


Oskar von Miller



Two-pole DC Motor

Early salient pole synchronous generators



Hefner-Alteneck´s salient pole synchronous generator

1878: *Hefner-Alteneck,* *Siemens & Halske, Nuremberg, Germany*

12-pole salient-pole synchronous generator with rotating coils as a two-phase system

Fixed stator permanent magnets as excitation

Axial-flux type machine

No iron core to avoid eddy currents as iron losses

Similar salient-pole synchronous generators with rotating DC excitation, iron core and stator ring coils by ***Gramme in Belgium****:* Four phase system

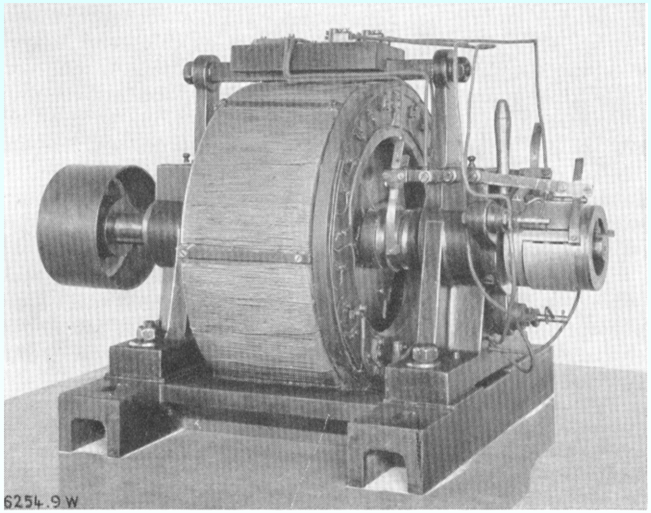
Multi-phase systems used only as separate single phase systems for electric lighting!

1. 1. History and significance of electric machinery

Early salient pole synchronous motors

1882 – 1888: Patents and prototypes of two-phase synchronous salient pole generators and motors by

- *Nicola Tesla, USA, Charles Schenk Bradley, USA, Friedrich A. Haselwander, Germany*



Friedrich A. Haselwander: His synchronous generator His synchronous 4-pole motor

The machines feature *Gramme´*s ring coils a stator winding.

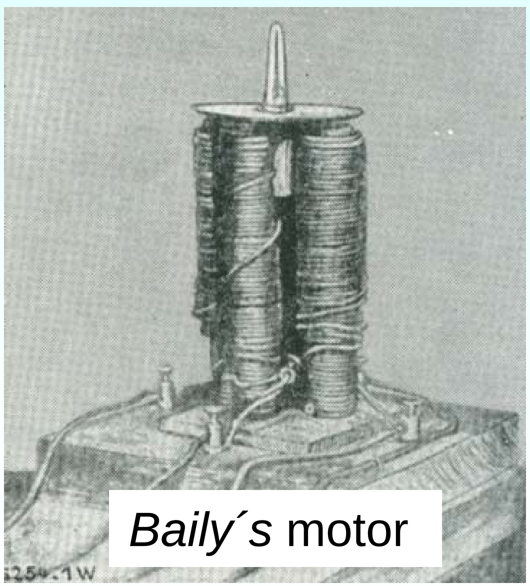
1. 1. History and significance of electric machinery

1824: *L. Arago, Paris, France*: A rotating magnet induces eddy currents in a copper disc, which also starts to rotate.

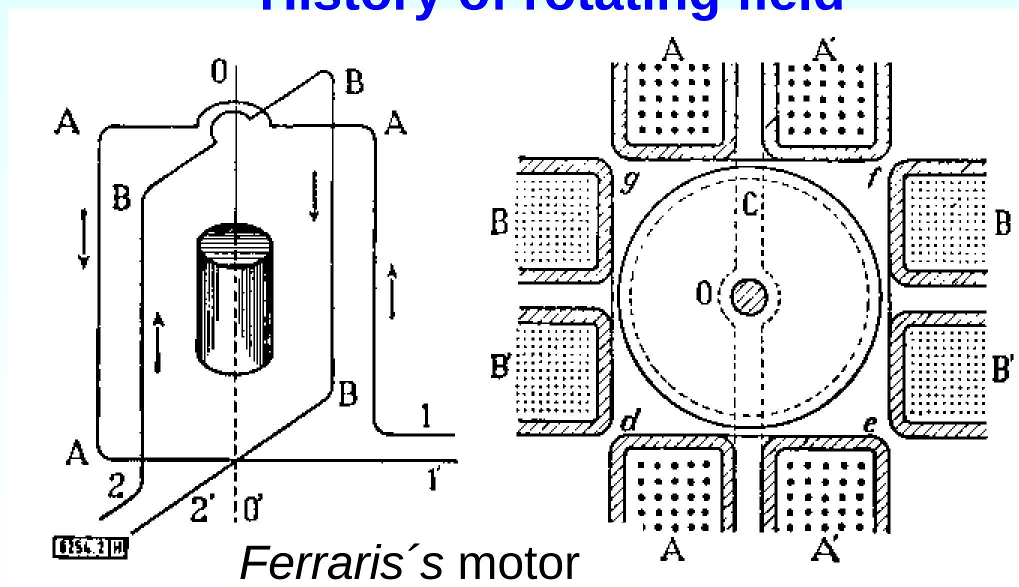
1879: *Walter Baily, London, England*: The rotating magnet field is generated by four coils on iron cores, where a DC current is switched from coil to coil.

1885: *Galileo Ferraris, Torino, Italy:* The rotating field is generated by two 90° shifted coils A, B, fed by a two-phase current system. Published in 1888, *G. Ferraris* predicts a maximum efficiency of 50%, which is wrong.

History of rotating field



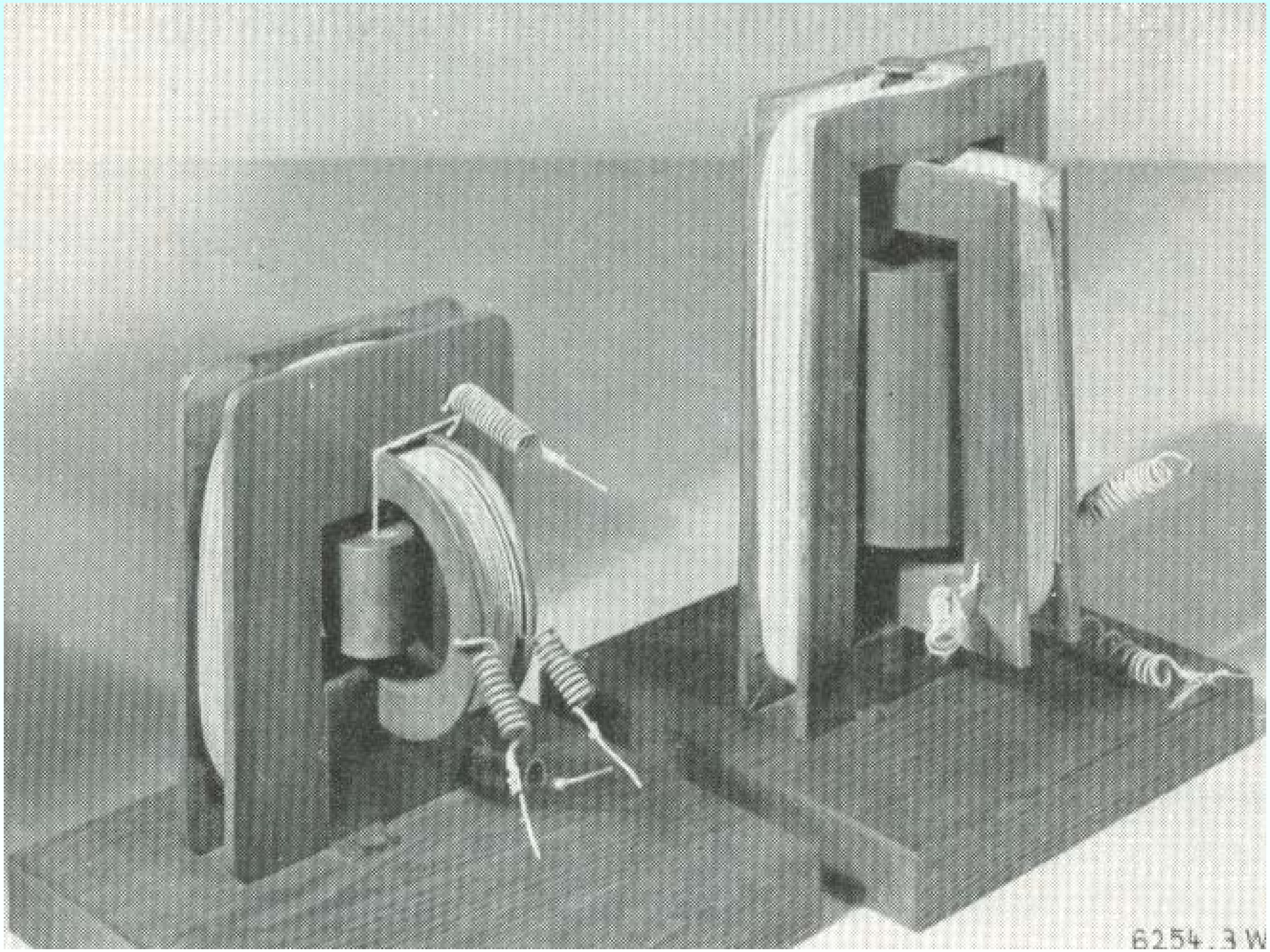
Baily´s motor



Ferraris´s motor

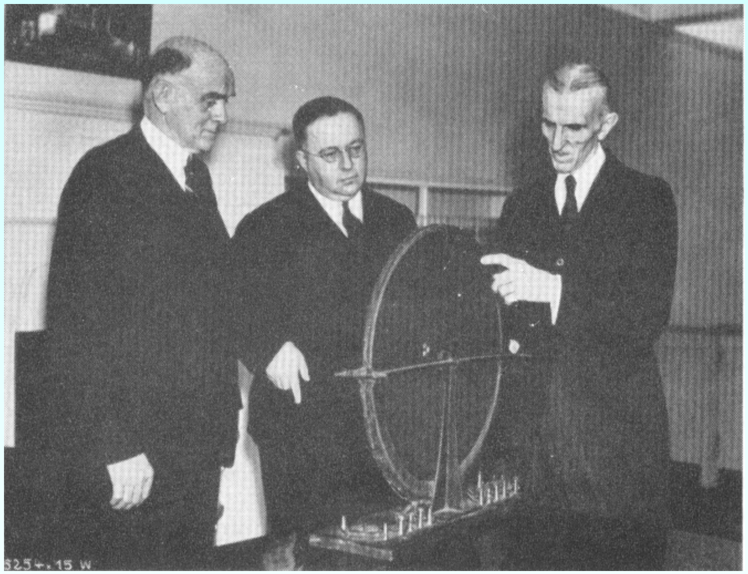
1. 1. History and significance of electric machinery

Early induction motors: Replicas of *Ferraris´s* motors (1885)

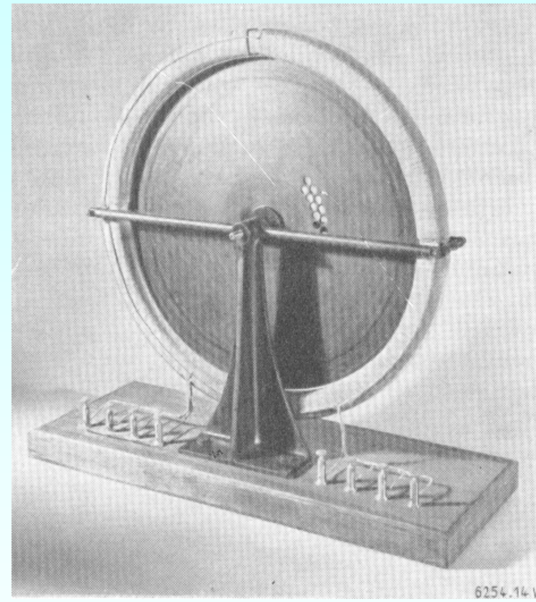


1. 1. History and significance of electric machinery

Nicola Tesla´s early induction motor (1887)



N. Tesla (right) presents his first iron disc induction motor in a later meeting. Photograph from *Tesla-Museum, Belgrade, Serbia.*



Replica of *N. Tesla´s* iron disc induction motor of 1887. Two-phase stator winding with *Gramme´*s ring coils

½ PS, 50% efficiency

1. 1. History and significance of electric machinery

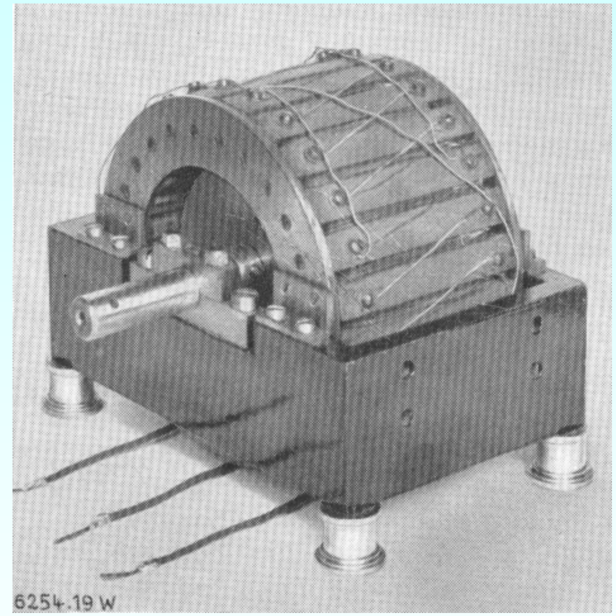
Michael v. Dolivo-Dobrowolsky´s first multi-phase cage induction motor (1889), rotor similar to modern motors

M. v. Dolivo-Dobrovolsky
1862-1919

-Stator: 24 *Gramme* ring coils, switchable to different phase numbers

-Rotor:
a) 24 copper bars with end rings in closed slots
b) 25 slots to minimize cogging

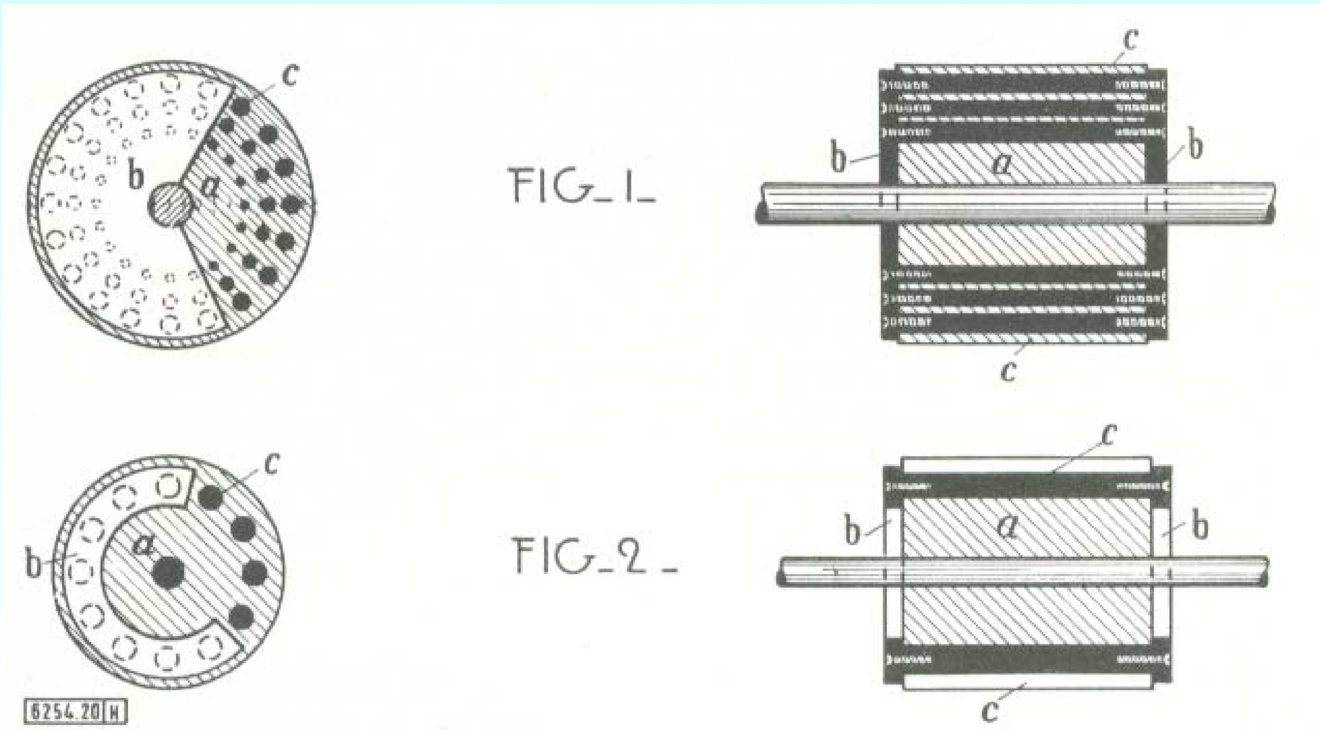
-Power 1/10 PS, efficiency 80%, operated with 3 stator phases



M. v. Dolivo-Dobrovolsky´s first cage induction motor of 1889.

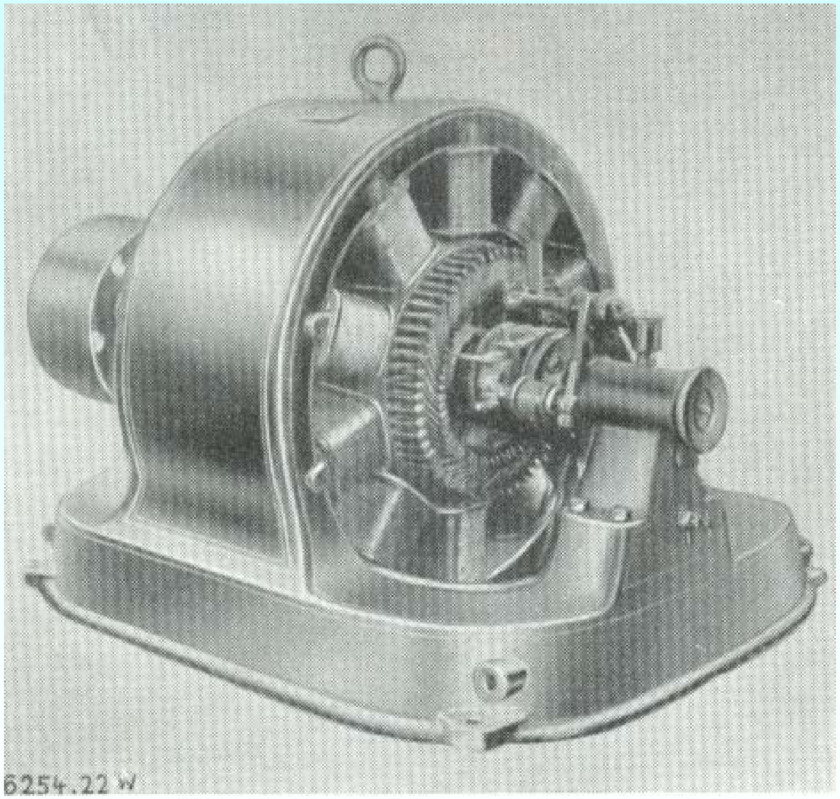
1. 1. History and significance of electric machinery

Patent drawings of thr squirrel rotor cage of *Michael v. Dolivo-Dobrowolsky´s* cage induction motor (1889), built at *AEG, Berlin*



1. 1. History and significance of electric machinery

Jonas Wenström´s first three-phase salient pole synchronous generator (1889), built at *ASEA, Sweden*



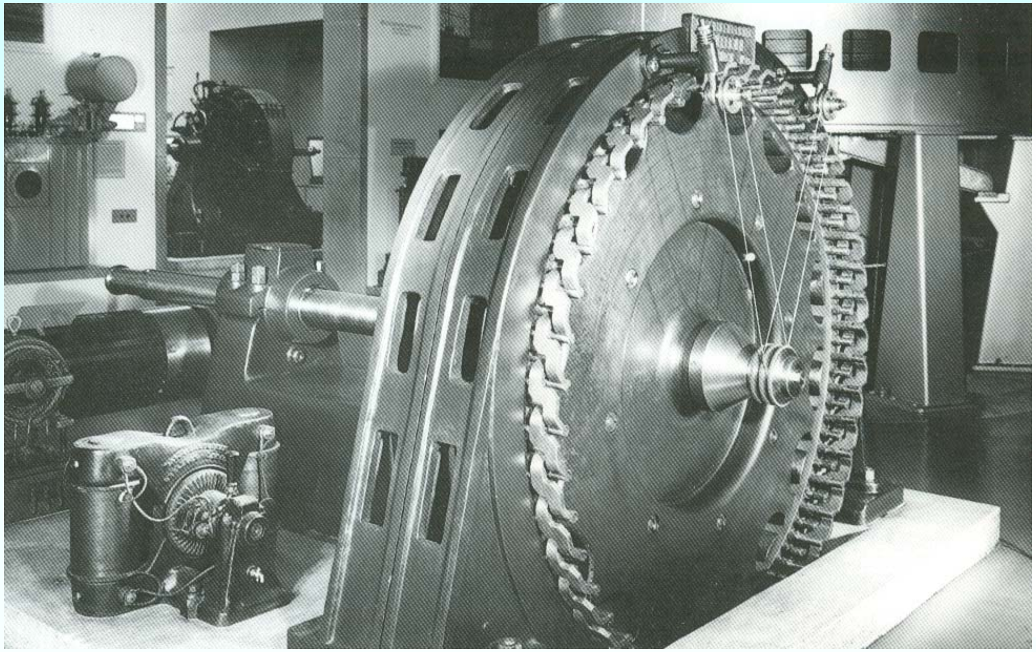
- 10 kVA, 10 poles, 420/min, 60 Hz

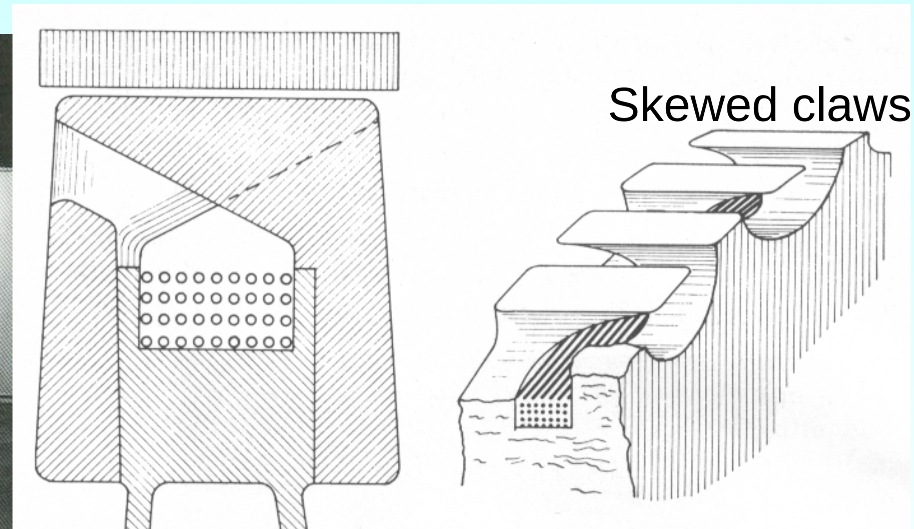
-Stator: Fixed electrically excited ten poles,

-Rotor: 3.phase distributed winding in slots, three slip rings to transmit the electrical power

1. 1. History and significance of electric machinery

1891: *Ch. Brown, M. v. Dolivo-Dobrovolsky*: First three-phase AC electrical power transmission: From *Lauffen/Neckar* to *Frankfurt/Main* via 175 km a power of 300 PS, 30 kV, 40 Hz was transmitted, based on an idea of *Oskar v. Miller*





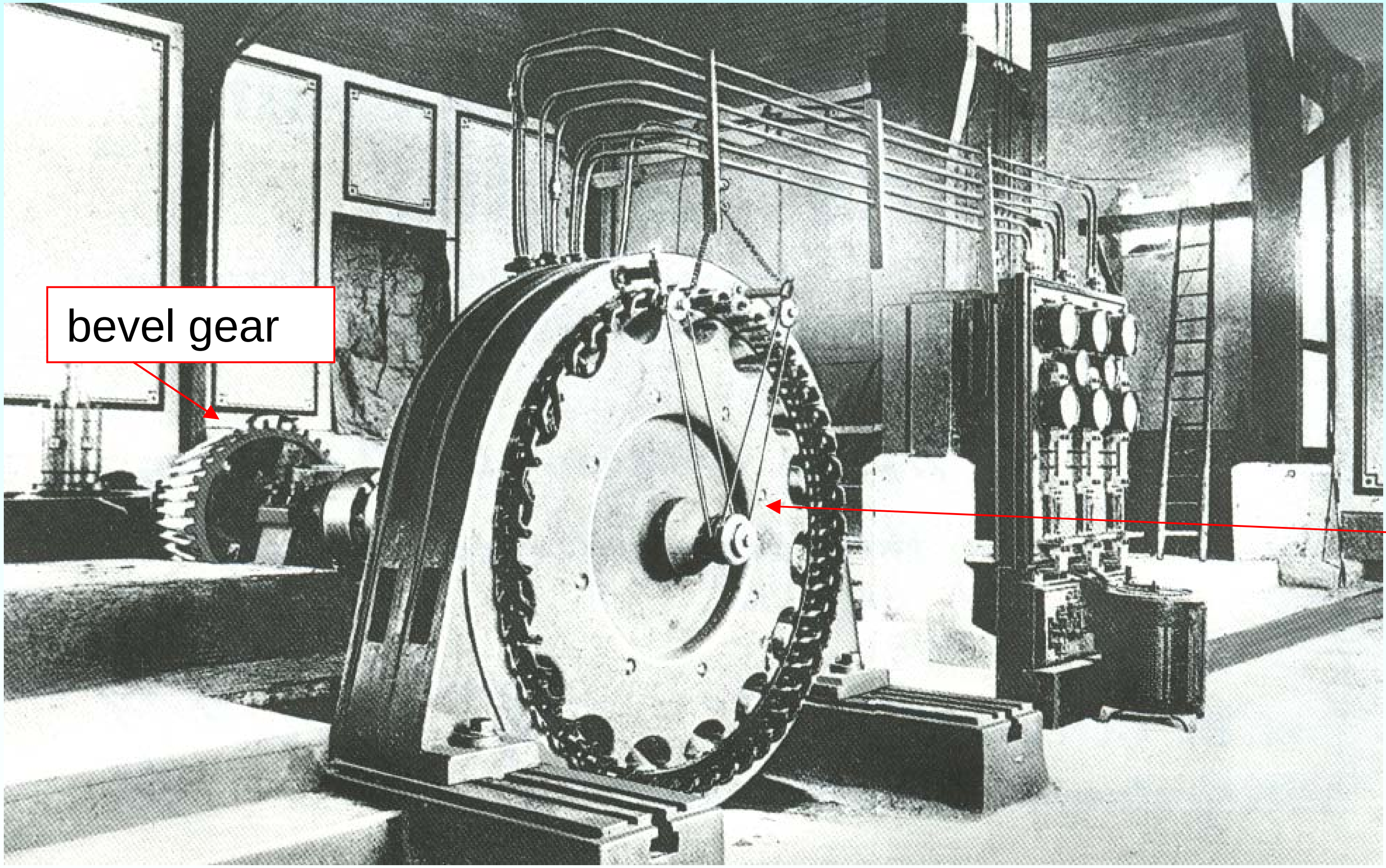
Claw-pole rotor, 32 poles formed by 32 claws, ring coil as excitation

Synchronous claw-pole generator, 210 kW, 95 V line, 1400 A, 150/min, 40 Hz, 32 poles, distributed stator winding, 3 phases, q = 1 slot per pole and phase, efficiency 96.5%

Generator design:
Ch. Brown, Maschinenfabrik Oerlikon, Switzerland

1. 1. History and significance of electric machinery

Lauffen/Neckar power station 1891

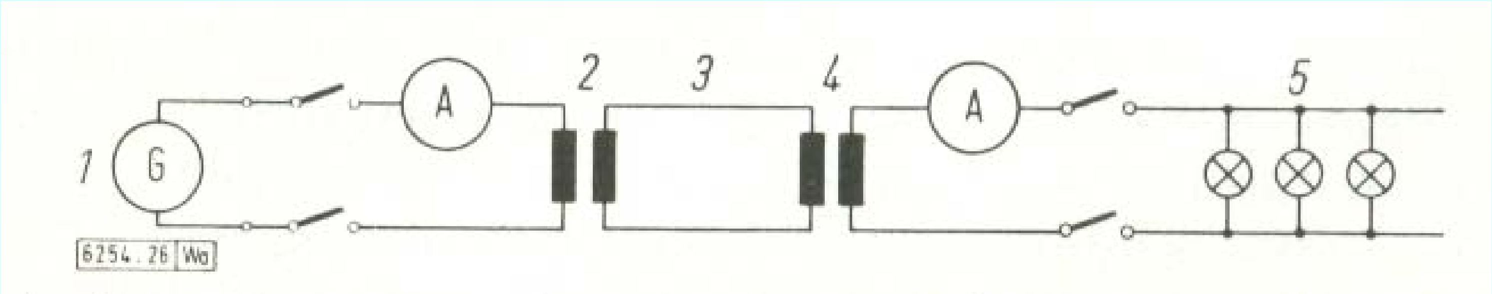


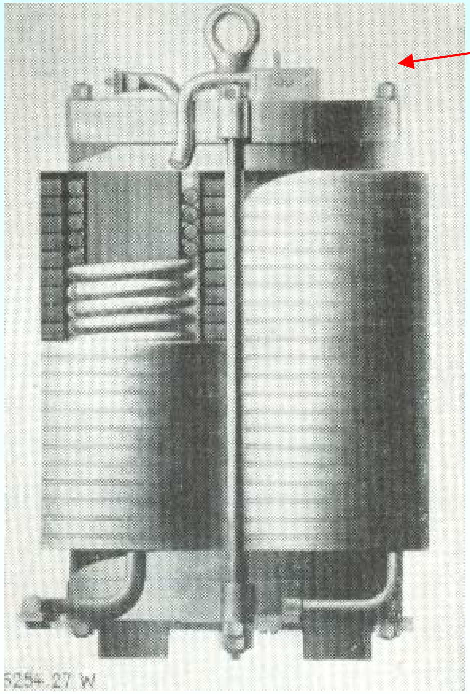
-Generator driven by a bevel gear

- Generator rotor excitation via metal rolls and metal ropes

1. 1. History and significance of electric machinery

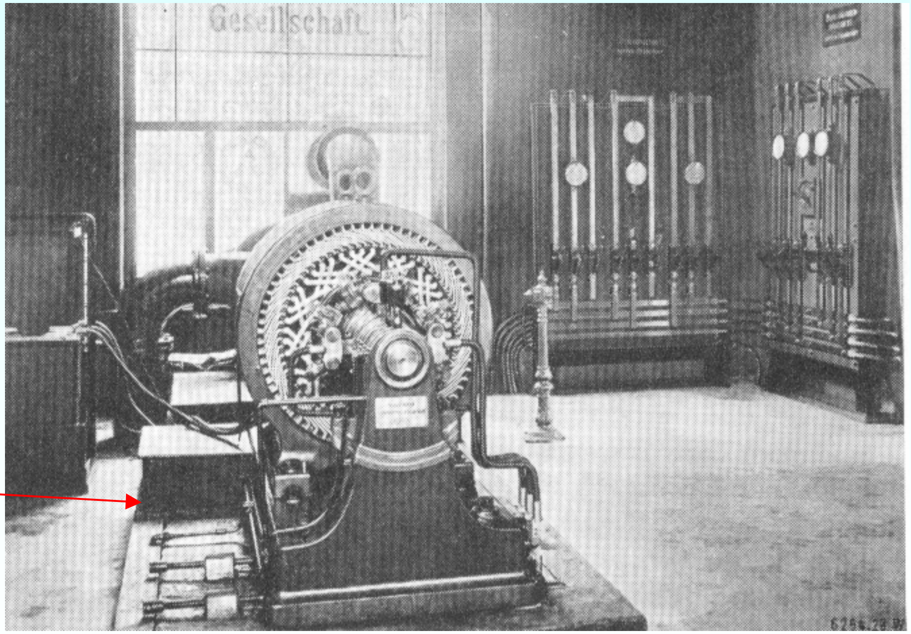
First 3-phase AC electrical power transmission: *Lauffen/Neckar* to *Frankfurt/Main*





(4): Oil-insulated 150 kVA/30 kV-transformer (AEG) at *Frankfurt*

(5): 100-PS-Slip ring induction motor (AEG) at *Frankfurt*, left: transformer



1. 1. History and significance of electric machinery

First 3-phase AC electrical power transmission:

Lauffen/Neckar to *Frankfurt/Main*

Operation results:

At 25 kV and 24 Hz a power of 180 PS was transmitted at an overall efficiency of 75%

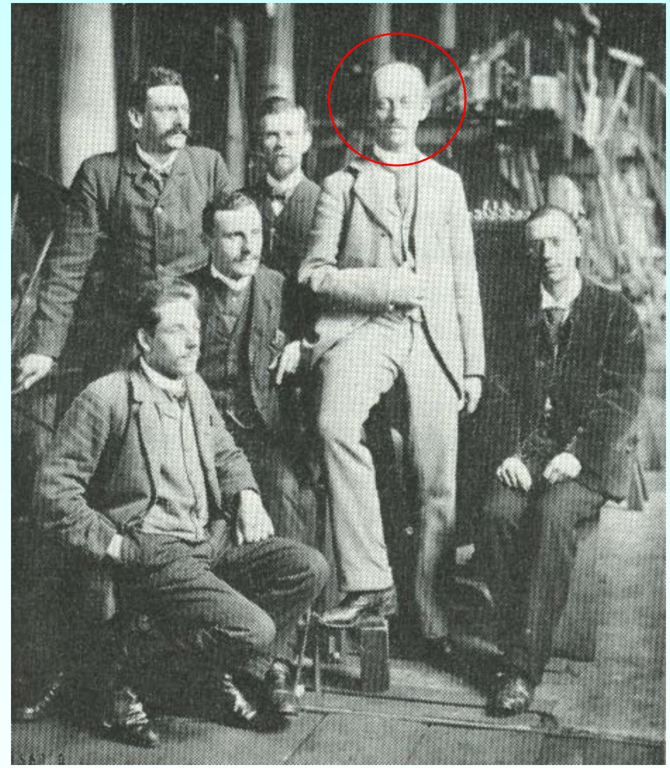
Visit of the *Lauffen* power station at the river *Neckar* (1891)

1. 1. History and significance of electric machinery

Michael von Dolivo-Dobrovolsky (1862-1919)

1885: With *Prof. Erasmus Kittler* at TH Darmstadt (now TU Darmstadt)

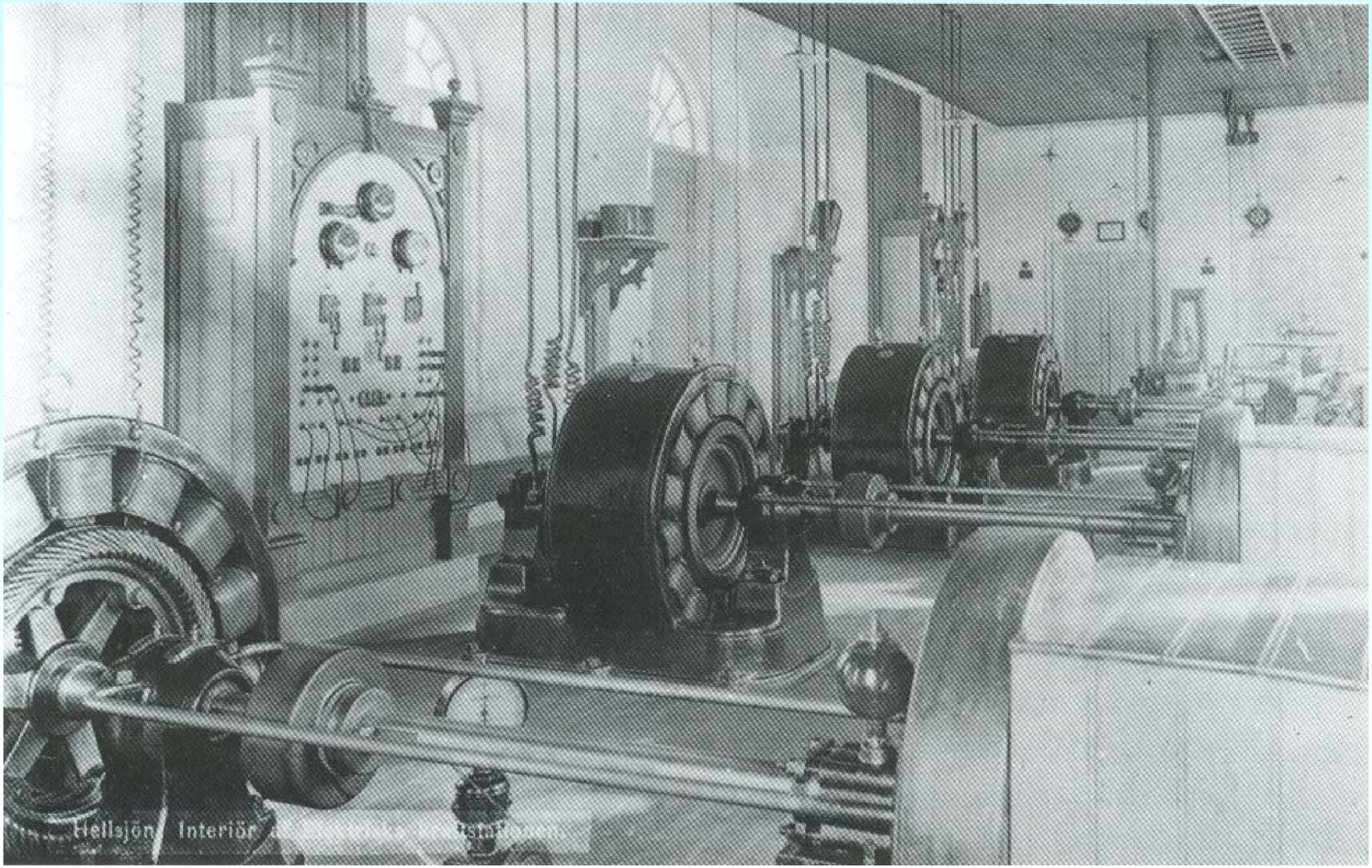
1900: At the age of 38 at AEG, Berlin



As director at AEG-Factory, Berlin, with colleagues

1. 1. History and significance of electric machinery

Hydro power plant *Hellsjön, Sweden*, 1893



Salient 16-pole synchronous generators

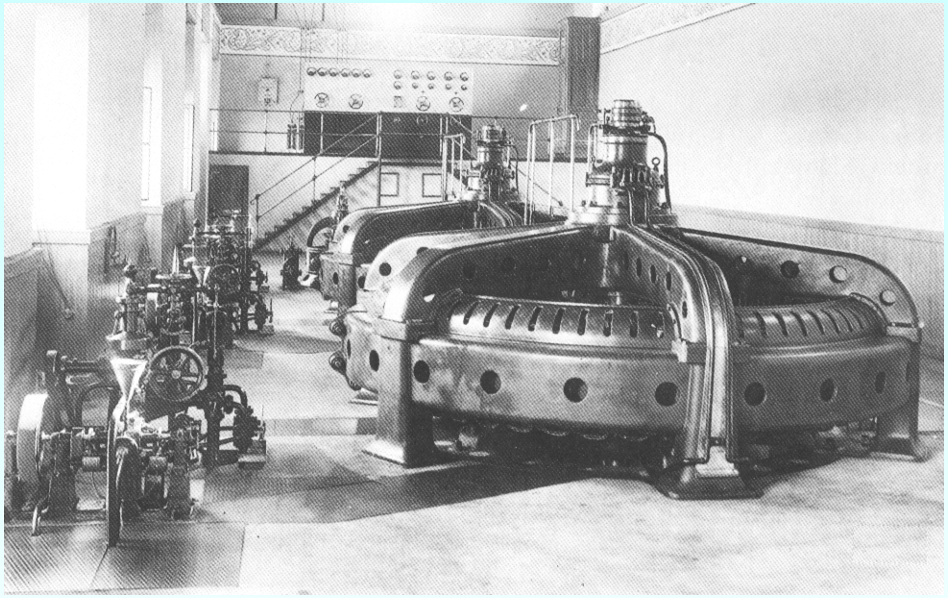
-Outer pole excitation

- Inner rotating two-layer three-phase distributed winding

-344 kVA:
High voltage transmission with 9.5 kV via 13 km to *Grängesberg*

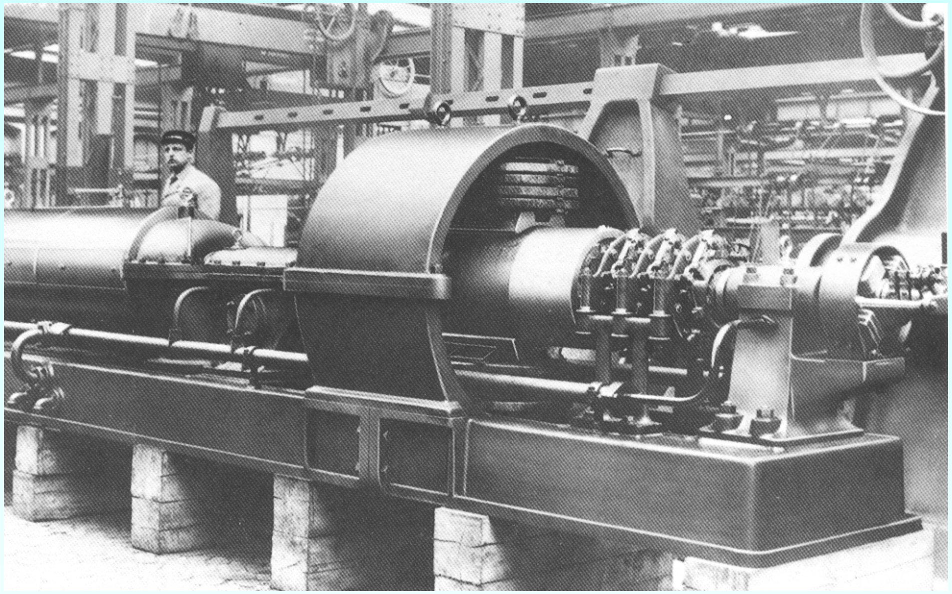
1. 1. History and significance of electric machinery

Early commercial synchronous generators



1903: **Hydro power plant** *Festi-Rastini, Milano, Italy*: Vertical shaft inner rotor salient 60-pole synchronous generators 600 kW, 84/min, 42 Hz

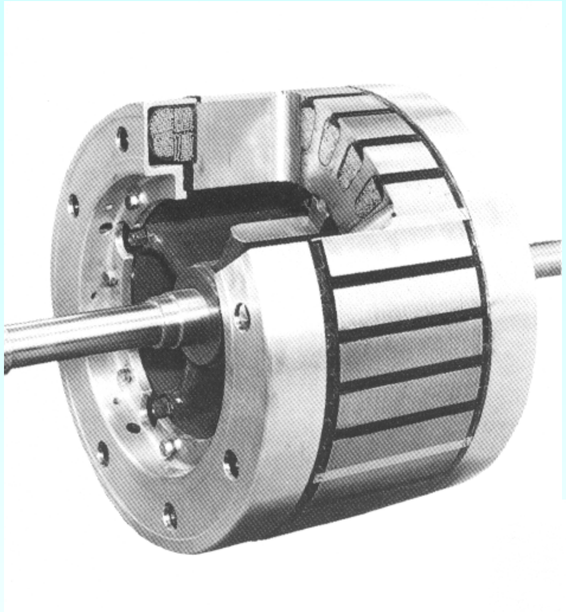
Vertical shaft generators first developed by *Ch. E. Brown* since ca. 1895



1901: **Steam power plant**: Horizontal shaft 2-pole synchronous generator, outer excitation, 3 slip-rings for rotating stator winding, 250 kW, 3000/min, 50 Hz, built by *Wild & Abegg, Torino, Italy*

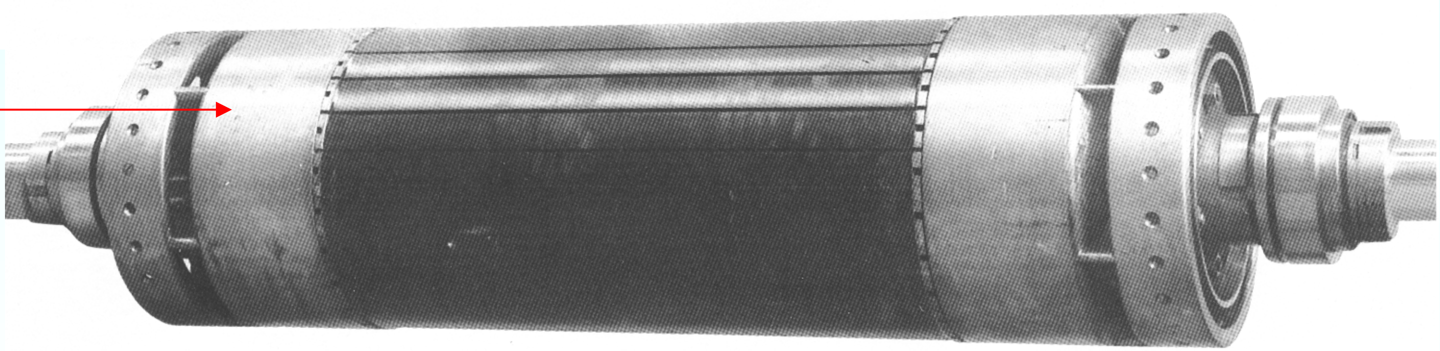
1. 1. History and significance of electric machinery

World´s first turbine synchronous generators (cylindrical rotor)



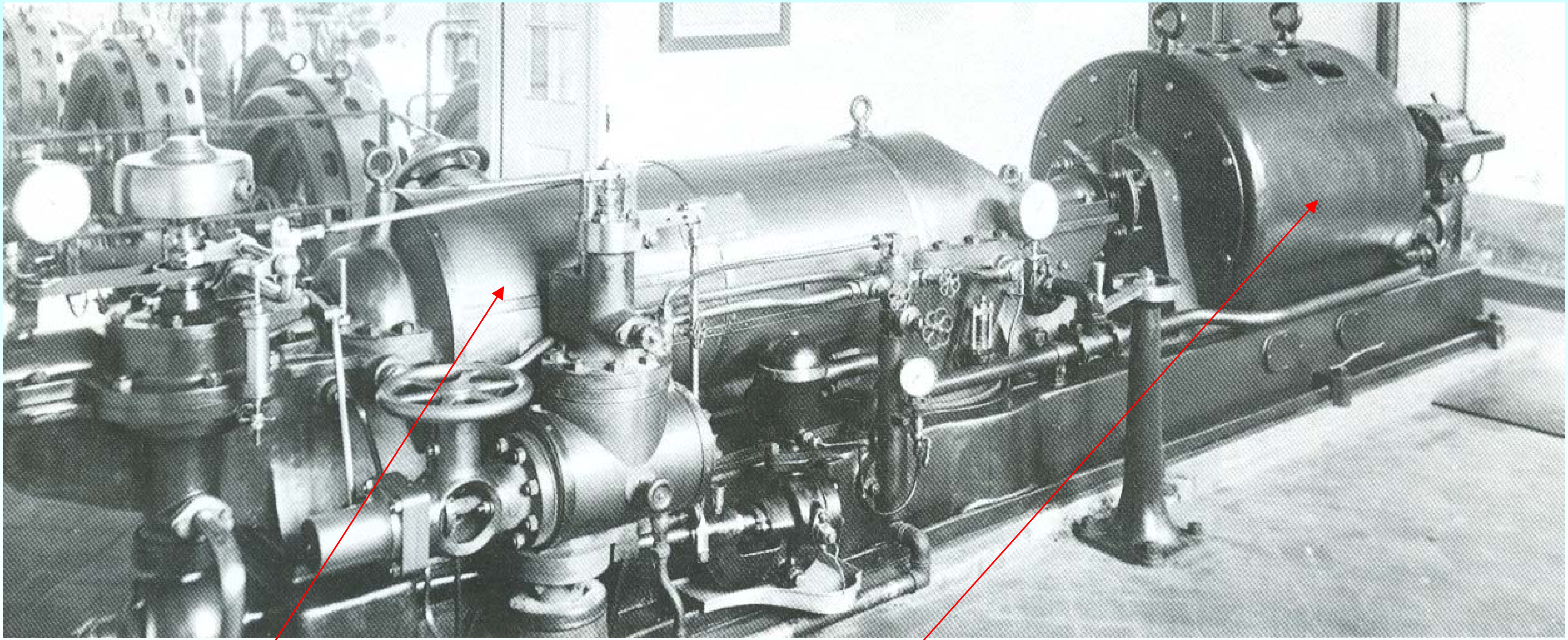
1898: Worlds first cylindrical synchronous rotor with six rotor poles, laminated iron core, 100 kVA, by *Ch. E. Brown*

1901: Worlds first two-pole cylindrical synchronous massive rotor, 250 kW, 3900/min, 65 Hz, by *Ch. E. Brown*



Non-magnetic retaining end caps for the rotor winding overhang

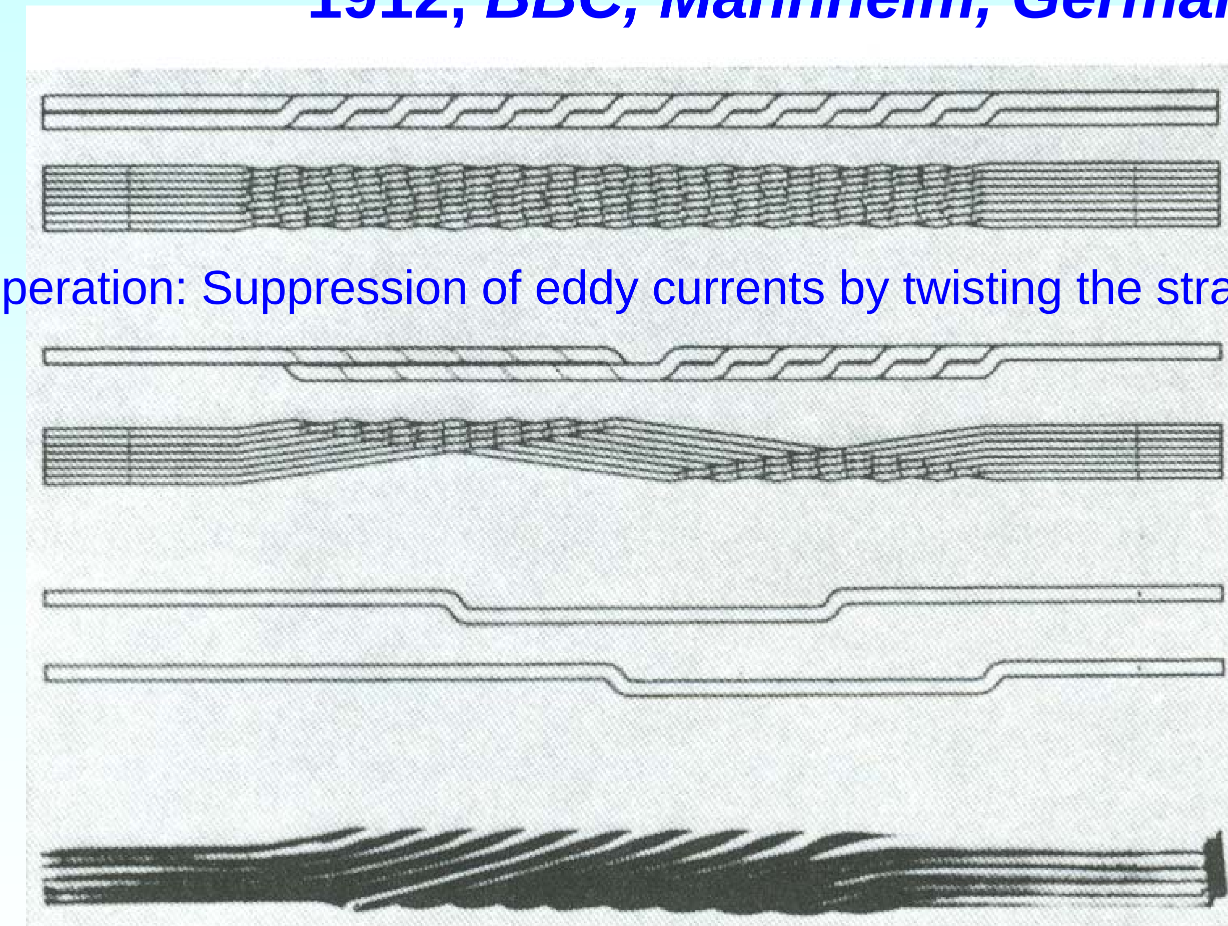
World´s first two-pole turbine synchronous generator with cylindrical massive rotor, *Ch. E. Brown*



1901: Steam turbine (*Parson*) and two-pole synchronous generator with cylindrical massive rotor, 250 kW, 3900/min, 65 Hz, *Chur* power station, *Switzerland*, by *Ch. E. Brown*

1. 1. History and significance of electric machinery

Twisted strands to form a rectangular bar, by *Ludwig Roebel*, 1912, *BBC, Mannheim, Germany*



Full bar top view

Full bar side view

AC operation: Suppression of eddy currents by twisting the strands

Half bar top view

Half bar side view

Two single strands top view

Completed bar (photograph)

Unification of grid frequency

- Grid frequencies differing very much until ca. 1920: 25 Hz … 60 Hz

- 41.7 Hz = 5000 changes of polarity per minute: 5000/(60x2) = 41.6667 Hz

-**Concentration in *Europe*:** Compromise 50 Hz (recommended by Austrian board of Electrical Engineers)

- Retrofit of older units with different frequencies lead to final unification

- ***United States, Japan***: Compromise 60 Hz:

  -*Example:* Power plant ***Niagara Falls***:
  Canadian side generators operated for long at 25 Hz, later mostly retrofit to 60 Hz

  - *Example:* ***Itaipu*** power plant, river Parana: Border line between *Brazil* (50 Hz), *Paraguay* (60 Hz): Half of the 18 generators operate with 50 Hz, and half with 60 Hz.

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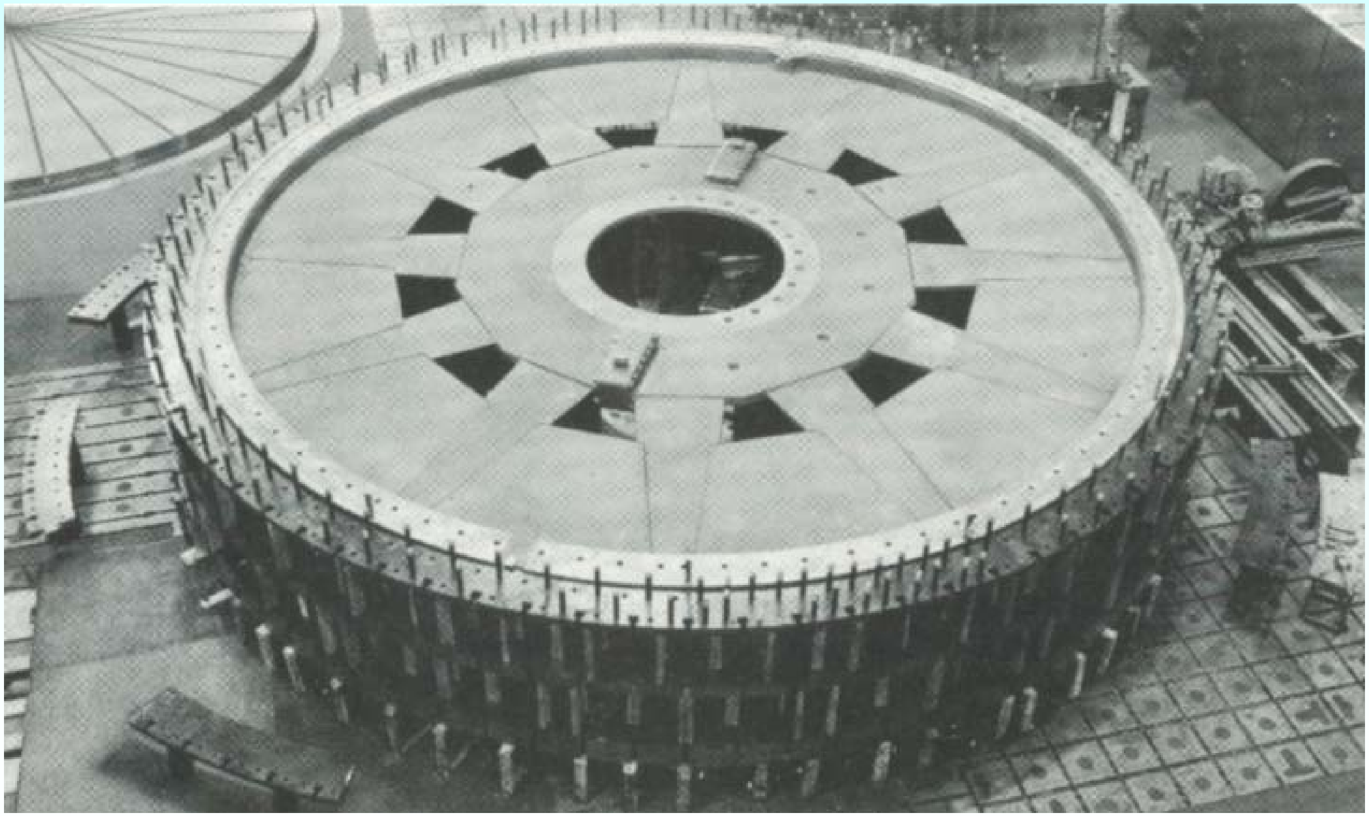
1. 1. History and significance of electric machinery

Mid-1920´s: Development of the first laminated, uniformely stressed rotor rim construction for vertical shaft hydro generators at *GE, USA*



Laminated rotor rim construction (mid-1950´s):

("Blechkettenläufer")

This removed many restrictions for the size of low-speed synchronous generators

All manufacturers have followed since this type of rotor design for large machines

Development of big power synchronous generators

- Steadily **increasing need** of electrical power due to increasing world population and increasing degree of electrification

- **World War II** gives big draw back to European technology progress, but US is booming

- **Mid-1950s:** Cold strip mill manufacturing of **low loss steel sheets** with grain orientation for power transformers developed in the USA

- **Large power plant projects** in the USA (hydro, thermal) set into operation: *Boulder Dam, Grand Coulee, Tennessee Valley Authority*

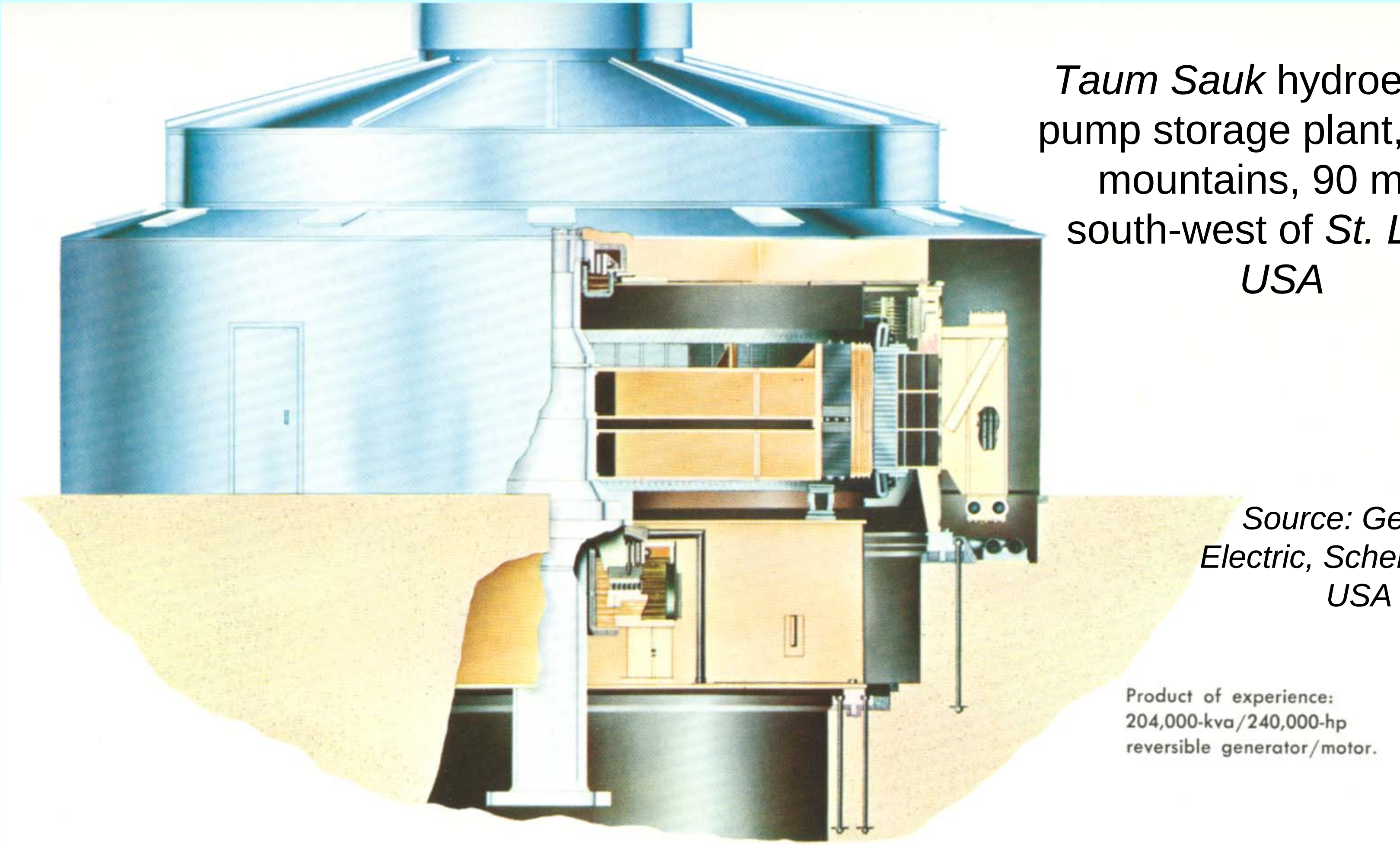
- Big machine units need **special bearing constructions** especially for vertical shaft hydro generators, which are the largest concerning rated torque and size

- **Mid-1950´s:** Development of civil use of **nuclear power** with power plants of steadily increasing size: Demand of big fast rotating two-pole and four-pole synchronous generators, driven by steam turbines

- **New cooling methods** necessary: Direct water cooling, direct hydrogen gas cooling

1. 1. History and significance of electric machinery

Ca. 1955: 204 MVA salient pole reversible motor-generator for pump storage plants, by that time one of the worlds largest machines

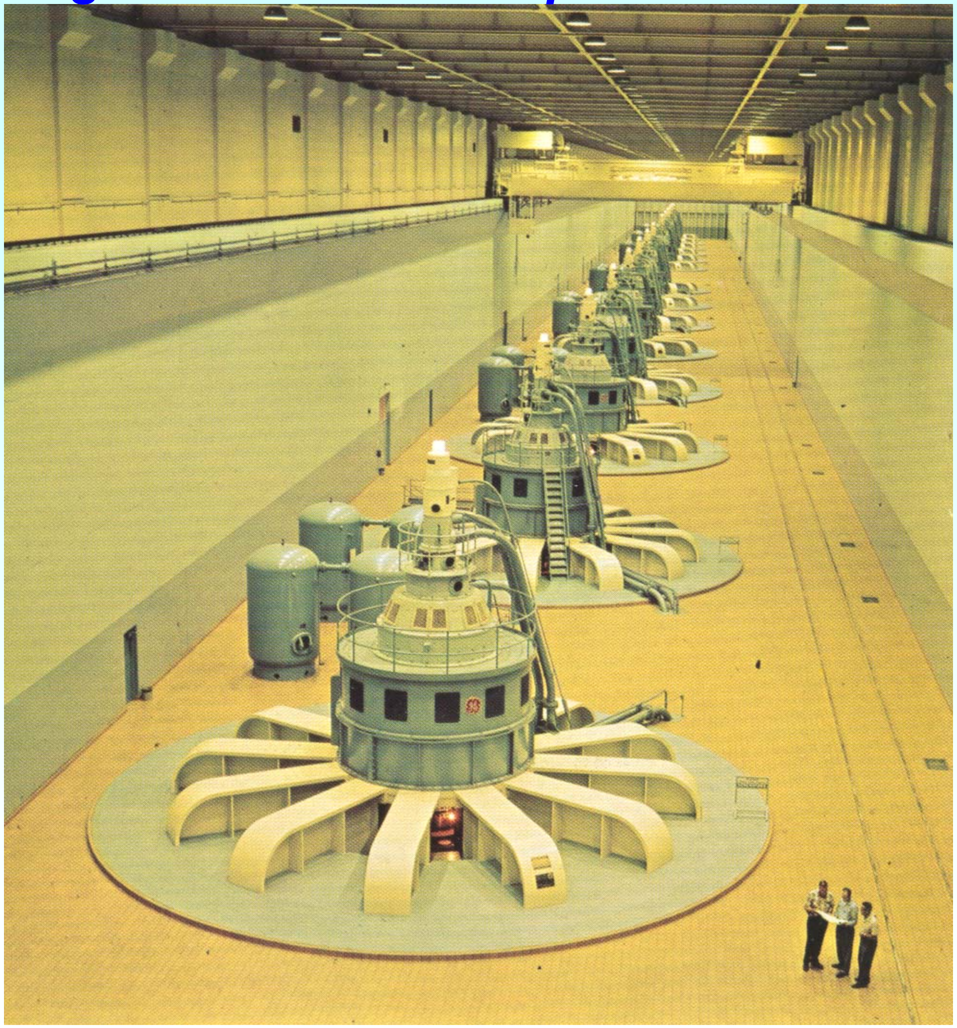


Taum Sauk hydroelectric pump storage plant, *Ozark* mountains, 90 miles south-west of *St. Louis, USA*

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Ca. 1955: 82.1 MVA salient pole vertical shaft hydroelectric synchronous generators with *Kaplan* turbines at *Columbia* river



The Dalles hydroelectric power station, *Columbia river, USA*:

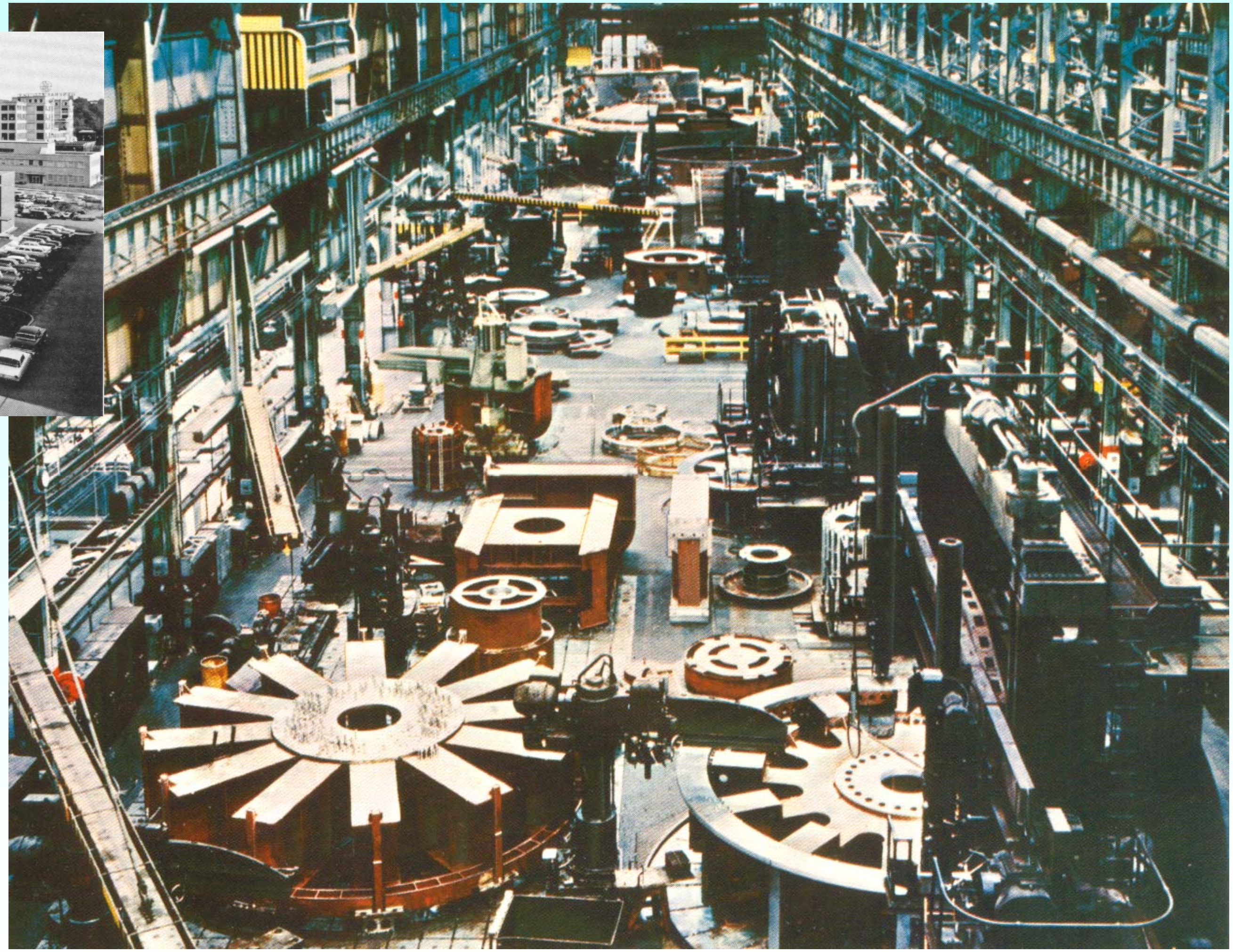
14 units, each 82.1 MVA, 60 Hz, 85.7/min, 84 poles

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

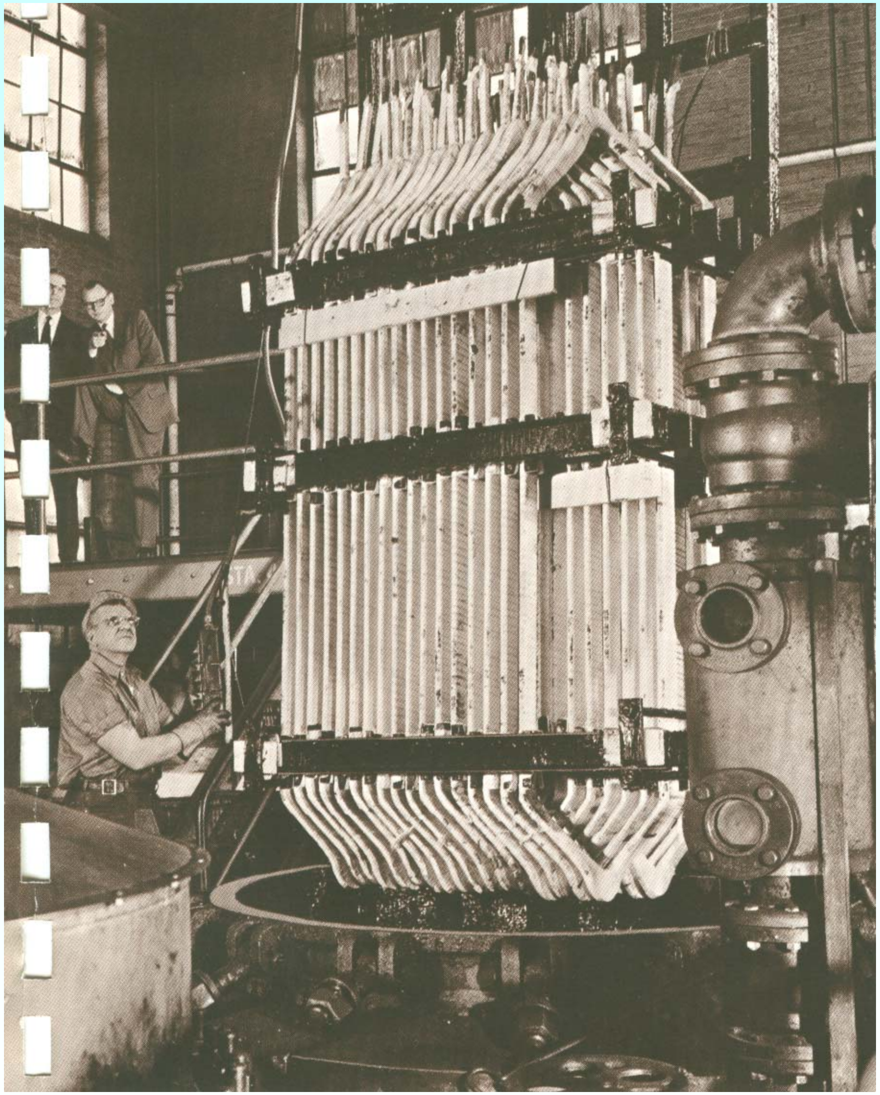
Ca. 1960: Manufacturing of salient pole vertical shaft hydroelectric synchronous generators at *General Electric Company*

Material & process laboratory, GE, Schenectady, ca. 1960



Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery



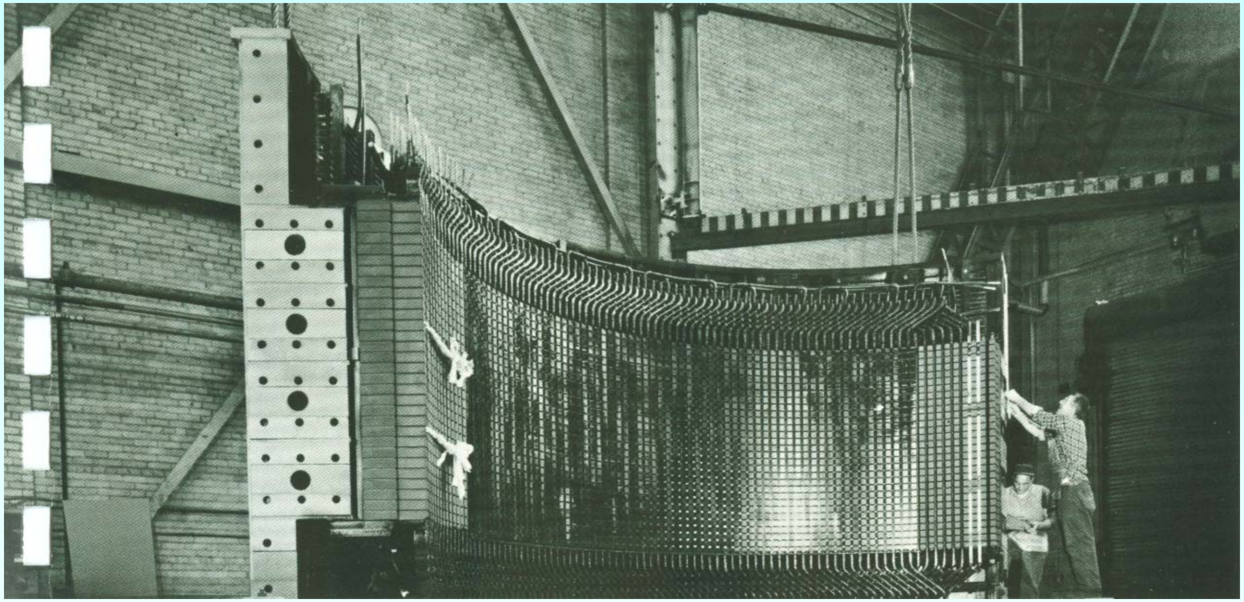
First vacuum and pressure-type compounding with applied mica tape for complete insulation of high-voltage coils at *GE, USA*

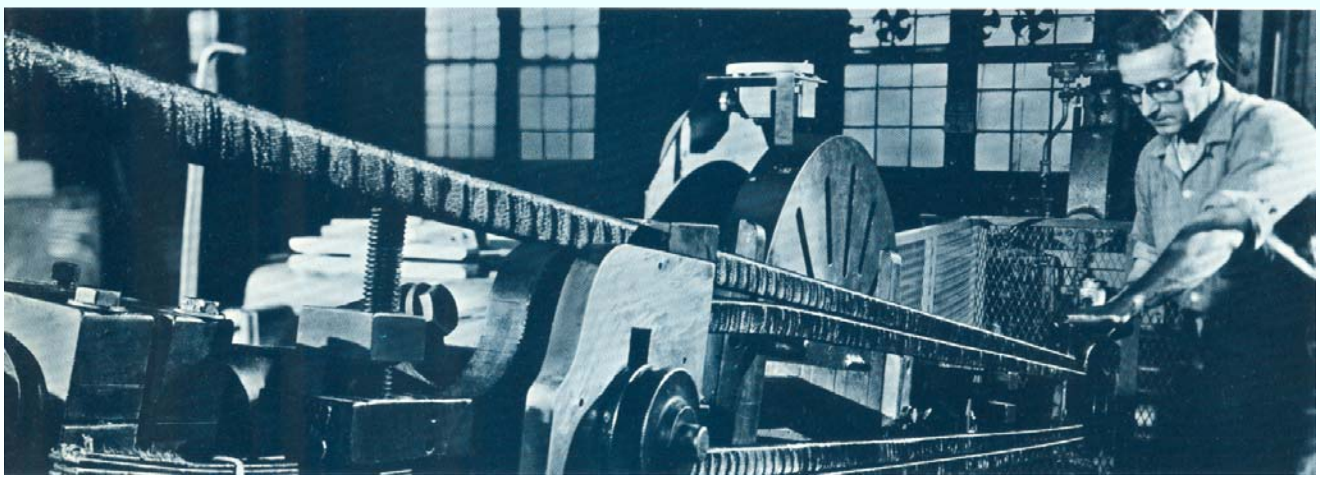
Vacuum and pressure-type compounding of coil insulation, *GE, USA,* mid-1950´s

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Ca. 1955: Manufacturing of salient pole vertical shaft synchronous generators



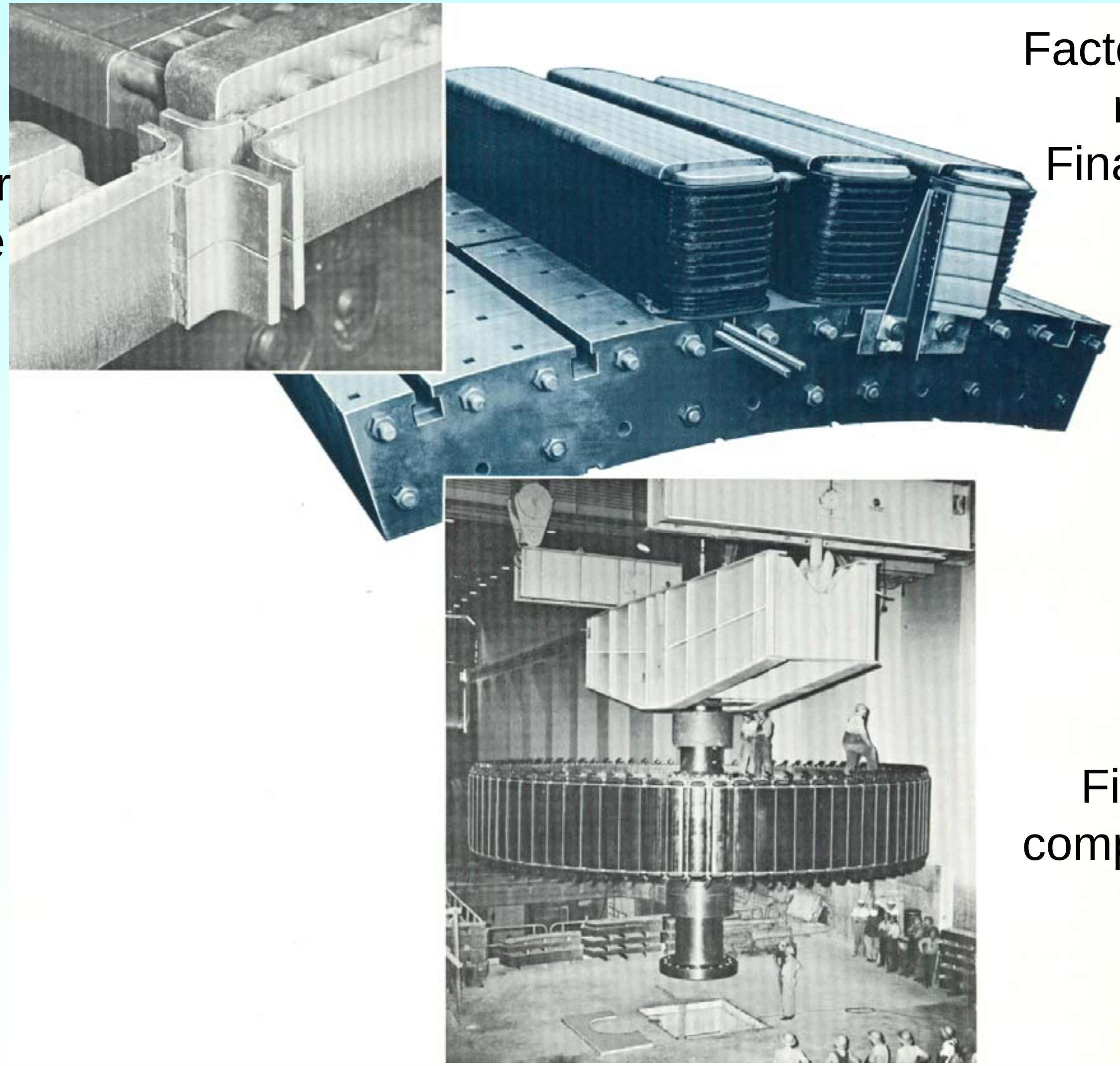


Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Ca. 1955: Manufacturing of salient pole vertical shaft synchronous generators

Heavy duty amortisseur winding = starting cage for starting pumped-storage units



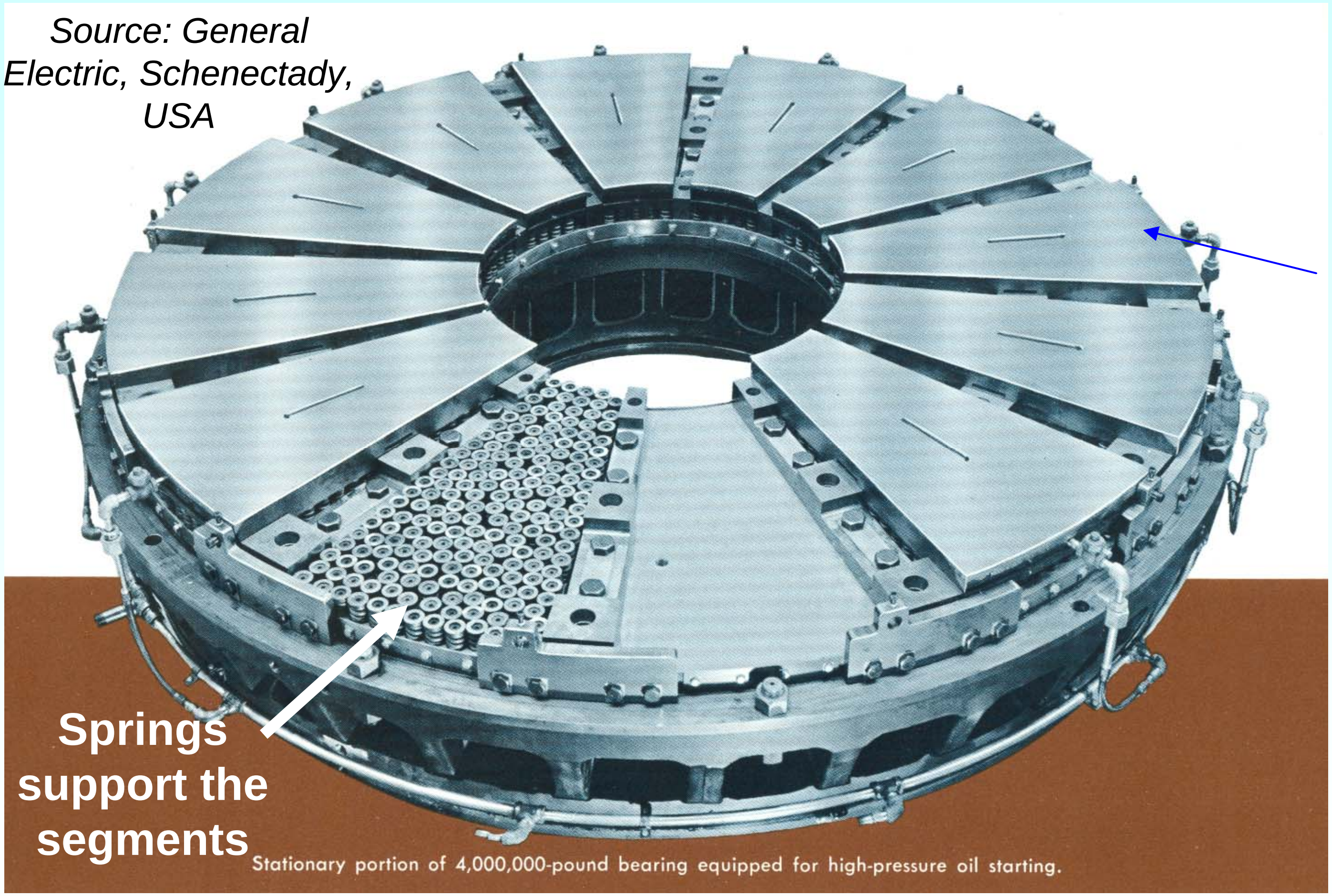
Factory trial assembly of rim, poles, fans:
Final assembly on site

Field assembly of completed rotor on-site

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

1953: <u>First</u> 4 mio. Pound thrust bearing operation at *McNary* dam (*Columbia* river) for vertical shaft synchronous generators



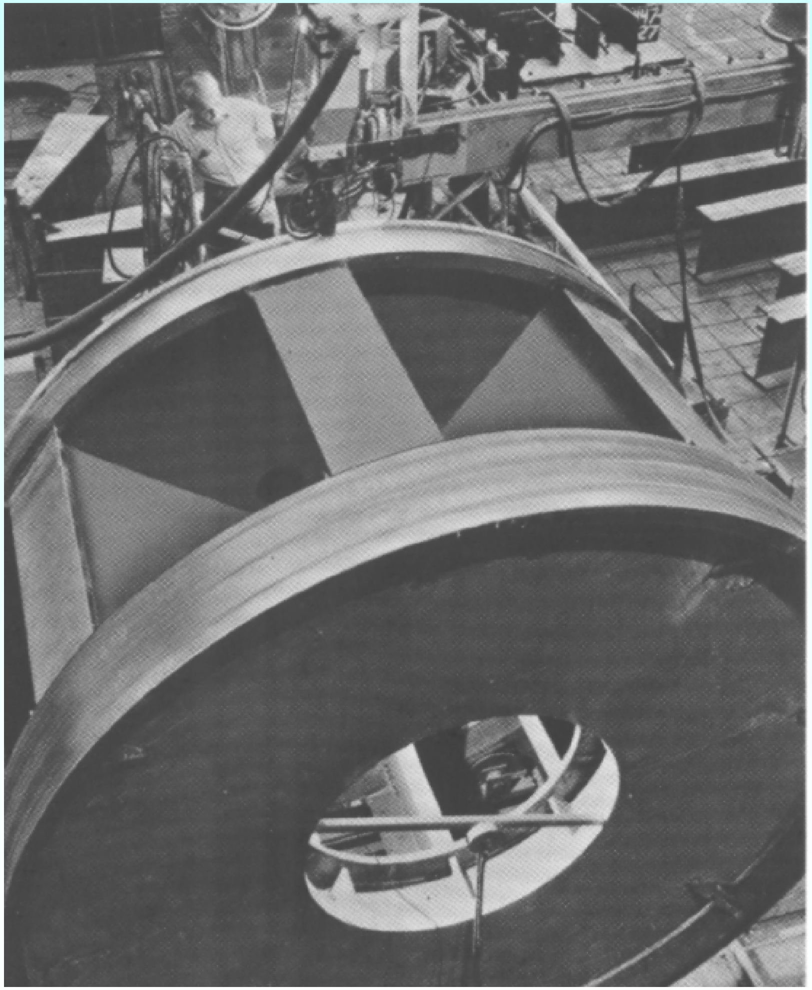
Spring-supported thrust bearing invented in 1916, *GE, USA*

Stationary portion of the 4 Mio. Pds. oil-lubricated segment thrust bearing for high pressure oil starting 73.6 MVA, 60 Hz, 85.7/min, 84 poles, *Kaplan* turbines

- Development of first high pressure self-starting thrust bearing at GE

- High-pressure-oil system reduces breakaway torque to very low values

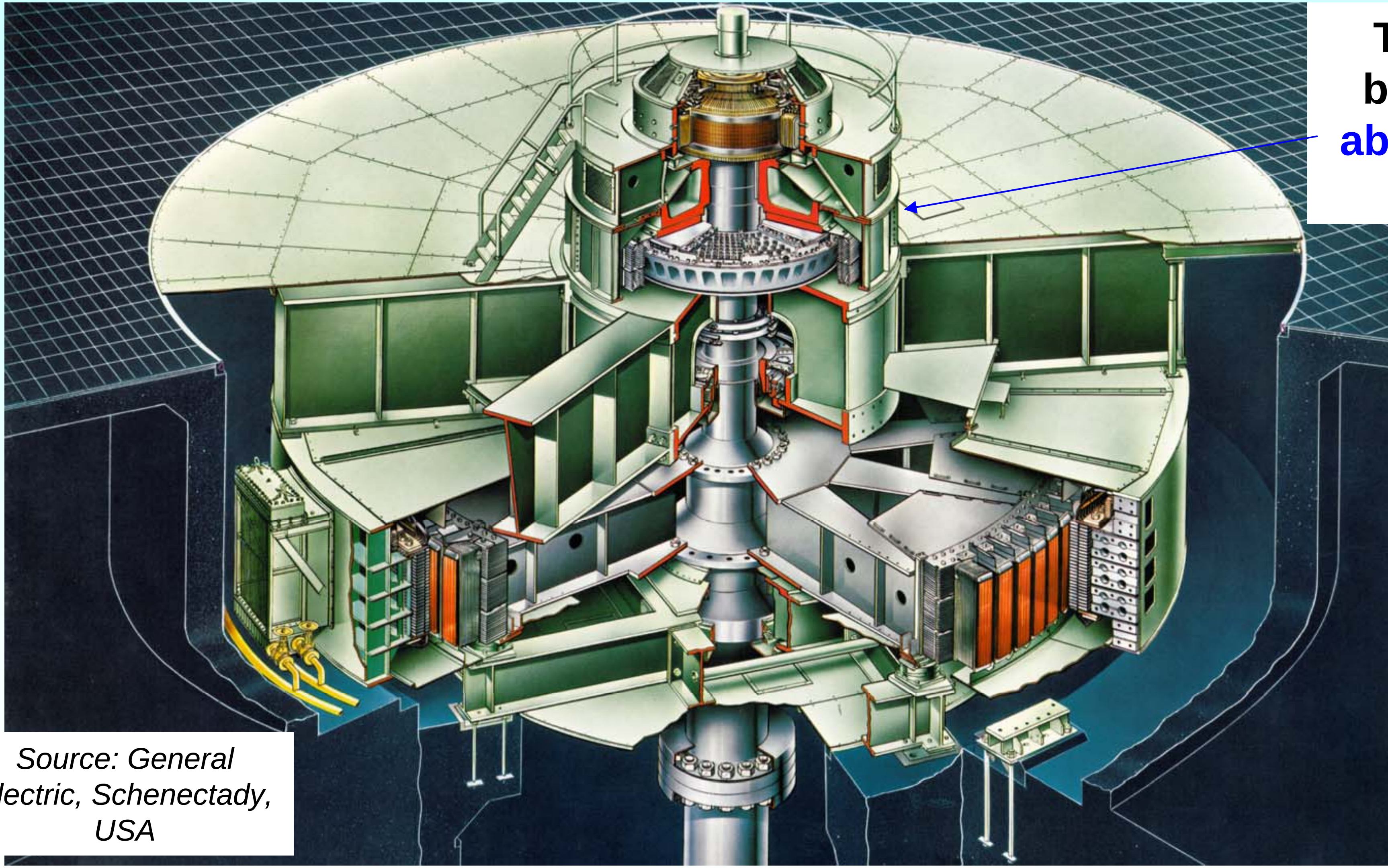
Submerged arc welding of upper bearing bracket hub, ca. 1960



Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Ca. 1960: Salient pole vertical shaft hydroelectric synchronous generators

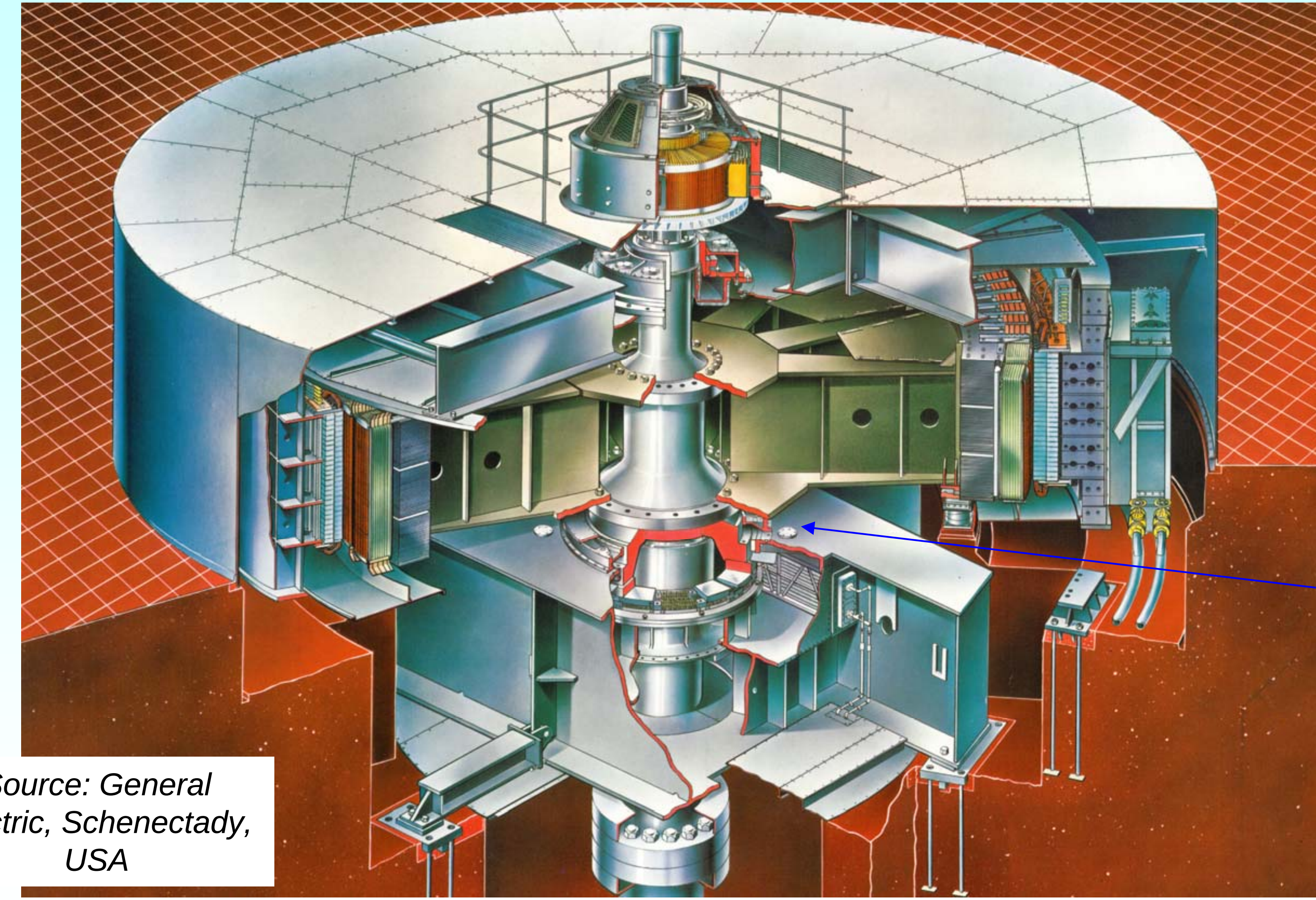


Thrust bearing above the rotor

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Ca. 1960: Salient pole vertical shaft hydroelectric synchronous generators



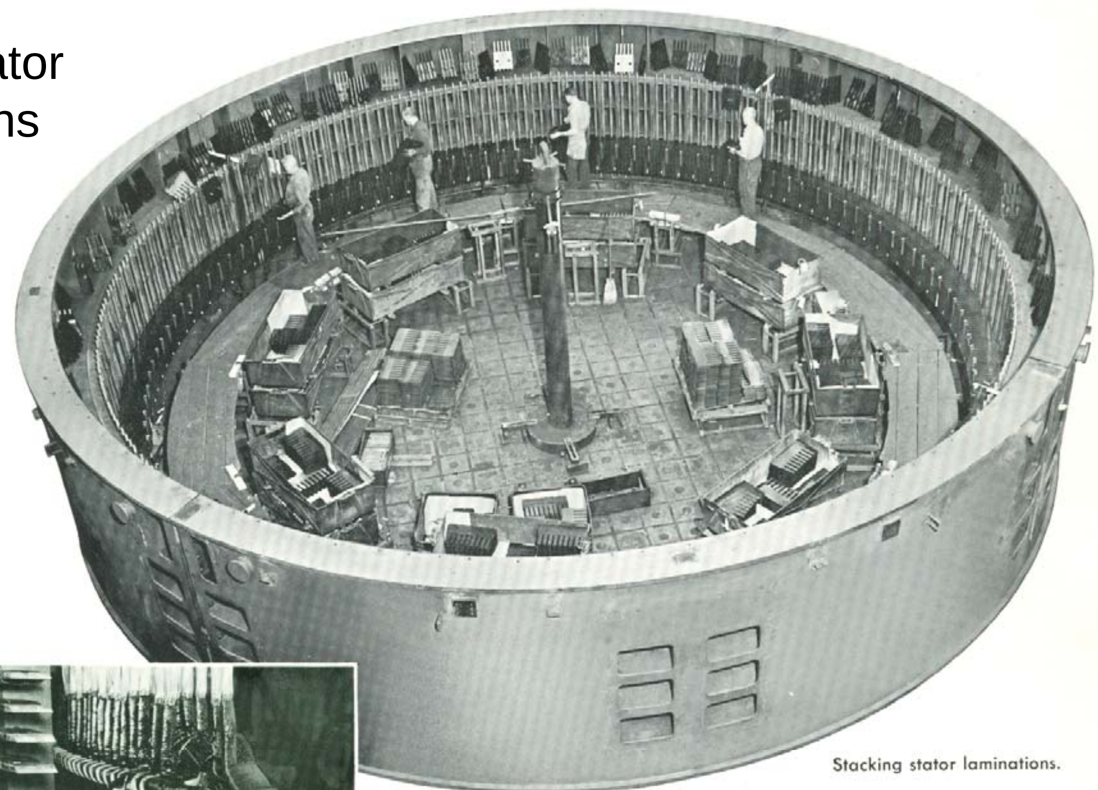
Thrust bearing below the rotor

Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

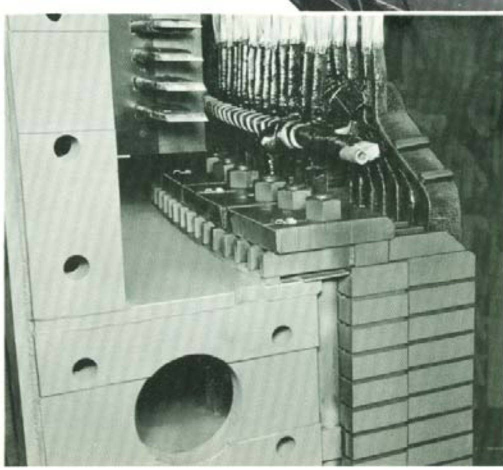
Ca. 1960: Manufacturing of the stator core and winding

Stacking the stator core laminations



Stacking stator laminations.

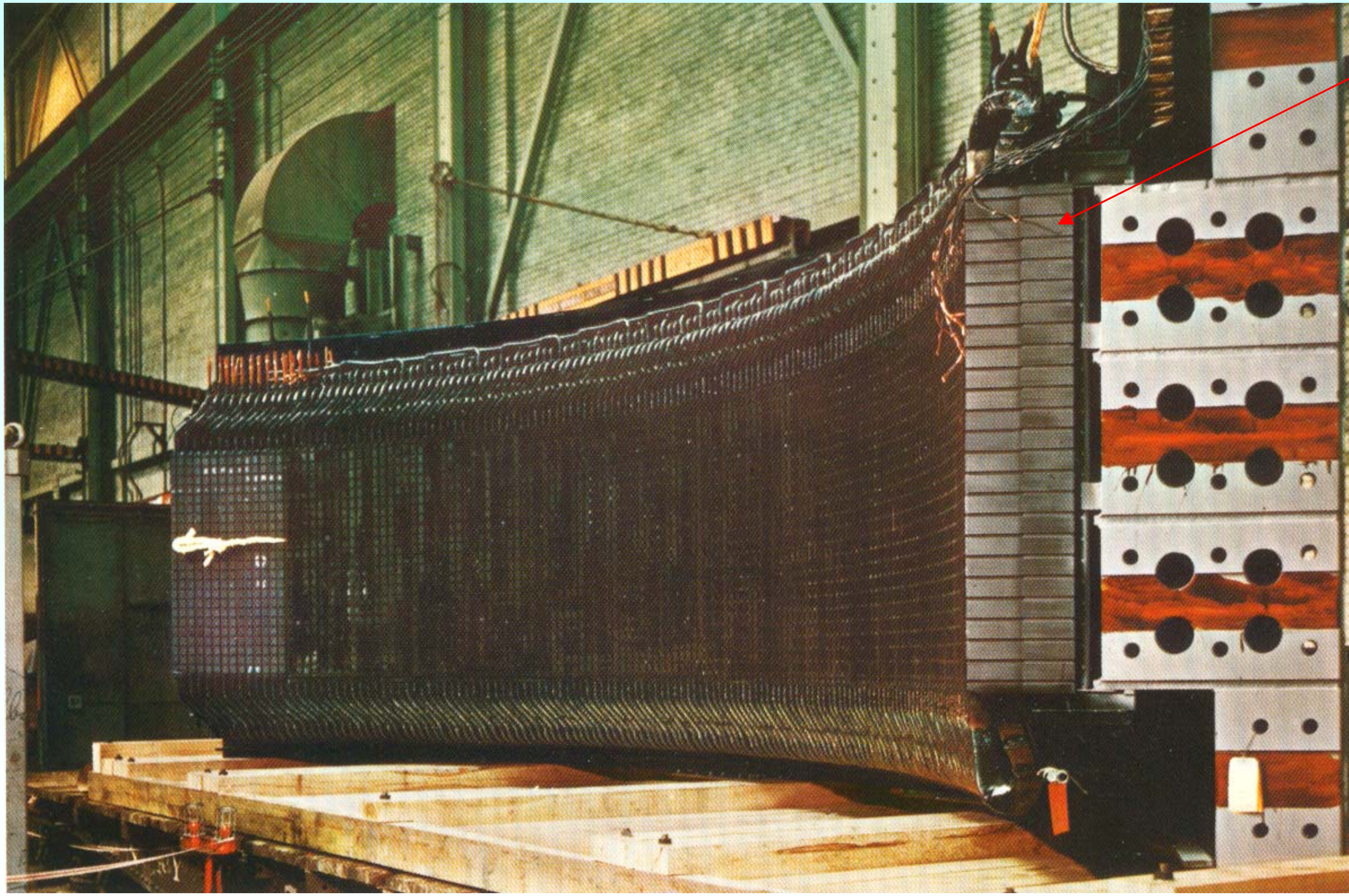
Source: General Electric, Schenectady, USA



Clamping flange assembly

1. 1. History and significance of electric machinery

Ca. 1960: The big stator hast be manufactured in sections for sake of transportation

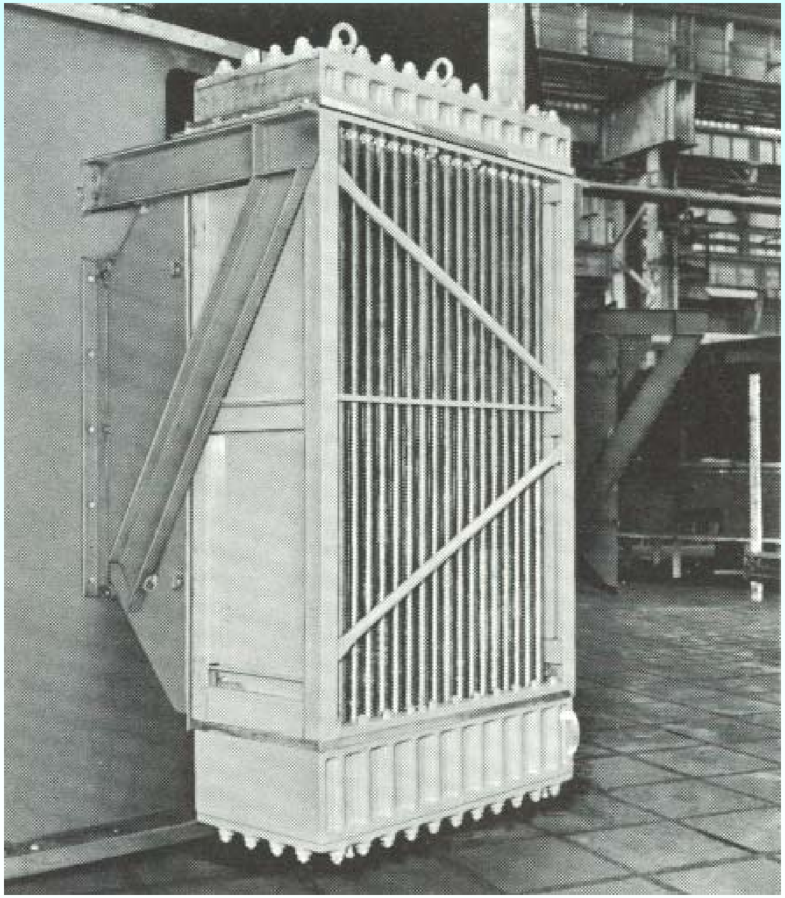


Completed stator sections

The sections are welded to form the stator ring directly at the site

Source: General Electric, Schenectady, USA

Ca. 1960: Surface air cooler for closed re-circulating cooling system



Source: General Electric, Schenectady, USA

1. 1. History and significance of electric machinery

Post-war development of large synchronous generators

- **Concentration** of large synchronous machinery in several big companies:

  Siemens AG takes over parts of the collapsed *AEG,* buys *Westinghouse* generator division, sells later hydro branch to *Voith*

  ASEA and *BBC* unite to *ABB*. The branch *ABB Power* is sold later to *Alstom*

  Alstom takes over *ABB* power and *GEC* in United Kingdom

  Andritz Hydro takes over *VA Tech Hydro*, which includes also *ELIN* generator business

- *Siemens* and *BBC* build the **world´s largest hydro generators** (e.g. 824 MVA, 90.9/min, 50 Hz, 66 poles) for *Itaipu*, *Parana* river (borderline between *Brazil* and *Paraguay*)

- ***Three Gorges Project, China***, is the world´s biggest hydro power plant (18 GW). *Voith-Siemens* and *Alstom* deliver the first generators. The technology is taken over big *Chinese* companies (e.g. at *Harbin*)

- *Siemens* delivers the **world´s largest 4-pole turbine generator (2 GW)** for the nuclear power plant *Olkiluoto, Finland*

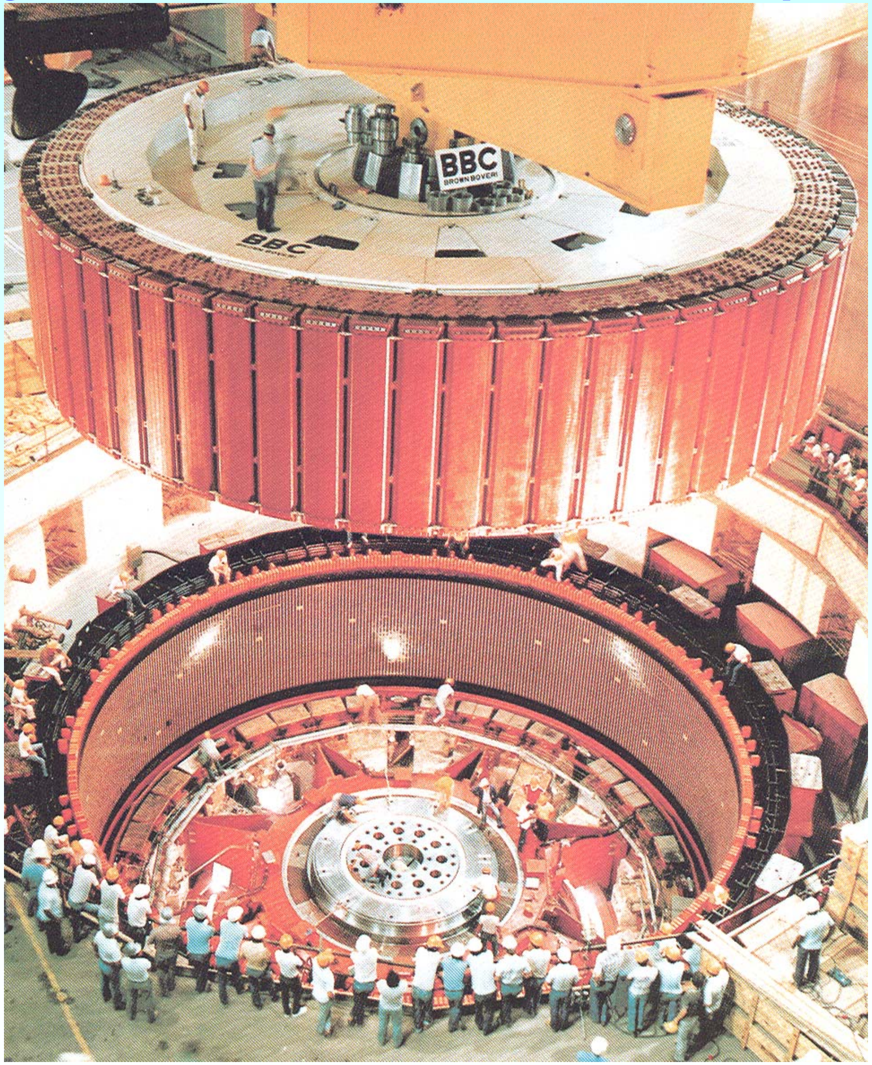
1. 1. History and significance of electric machinery

Largest hydro synchronous generators: *Itaipu, Parana* river, 14 GW

	Paraguay	*Brazil*
Grid frequency	**50 Hz**	**60 Hz**
Generator power	**823.6 MVA**	**737 MVA**
Speed / Stator voltage	**90.9/min / 18 kV**	**92.3/min / 18 kV**
Pole count / Torque	**66 / 74.59 MNm**	**78 / 73.46 MNm**
Power factor	**0.85 over-excited**	**0.95 over-excited**
Generator efficiency	98.6 %	98.6 %
Mech. input power	710 MW	710 MW
Generator transformer	**825 MVA**	**768 MVA**
Transformer voltage	18 kV / 525 kV	18 kV / 525 kV
Francis turbine	715 MW / 700 m^3/s	715 MW / 700 m^3/s
Turbine efficiency	93.8 %	93.8 %
Number of units	10	10

1. 1. History and significance of electric machinery

Mounting the rotor into the stator at *Itaipu, Parana* river, 14 GW



Hydro generator for 50 Hz,
66 poles, 824 MVA,
90.9/min, *Francis* turbine

Source: BBC (now Alstom Power), Switzerland

1. 1. History and significance of electric machinery

Total view of *Itaipu* hydro power plant, *Parana* river, 14 GW

Left part:

Spillway for water overflow

Power station in the center

Source: Wikipedia

Ca. 1980: View of *Itaipu* hydro power plant under construction, *Parana* river

On top of the 7.6 km long dam

12.8 Mio. m^3 of concrete were used for the project

Source: Wikipedia

1. 1. History and significance of electric machinery

View of barrage lake of hydro power plant *Itaipu*, *Parana* river

Size of barrage lake:

Area: 1350 km^2

Length: 170 km,

Average width: 7 km

Maximum height:112 m

29 billion tons of water

Source: S. Krauter, Wikipedia

1. 1. History and significance of electric machinery

Dam view of *Itaipu* hydro power plant, *Parana* river, 14 GW

Source: S. Krauter, Wikipedia

At the bottom of the dam: dam height 196 m, white water intake tubes of the 18 (now 20) *Francis* turbines (715 MW each)

1. 1. History and significance of electric machinery

Stored potential energy in the barrage lake of *Itaipu* hydro power plant

$$W_{pot} = \left(\frac{h_{ul} + h_{ip}}{2} - h \right) \cdot \gamma_{H_2O} \cdot g \cdot A \cdot (h_{ul} - h_{ip})$$

$$W_{pot} = \left(\frac{222 + 187}{2} - 86 \right) \cdot 1000 \cdot 9.81 \cdot 1350 \cdot 10^6 \cdot (222 - 187) = 54.93 \cdot 10^{15}\, J$$

W_{pot}: potential water energy relative to lower water level
h_{ul}: upper lake level: 222m above sea level
h_{ip}: penstock inlet height above sea level: 187m, h: lower water level: 86 m

A: lake area: 1350 km^2, γ_{H2Ol}: mass density of water

η_T =0.938 turbine efficiency, water flow: 700 m^3/s

$$P_T = \left(\frac{h_{ul} + h_{ip}}{2} - h \right) \cdot \gamma_{H_2O} \cdot g \cdot \dot{V} \cdot \eta_T = 118.5 \cdot 1000 \cdot 9.81 \cdot 700 \cdot 0.938 = 763 MW$$

$$P_{T,real} = 715 MW$$

Source: S. Krauter, Wikipedia

1. 1. History and significance of electric machinery

View of hydro generator shaft, *Itaipu* power plant, *Parana* river, 14 GW

Stator bore diameter: 16 m,

active iron length 3.5 m

Total rotating mass: 2650 tons

Source: S. Krauter, Wikipedia

1. 1. History and significance of electric machinery

View of generator hall and control center, *Itaipu* power plant, *Parana* river

Size of the machine hall:
Length: 986 m, Width: 99 m, Maximum height:112 m

Source: Wikipedia

Red Line: Border between *Paraguay* and *Brazil*

1. 1. History and significance of electric machinery

Two of the three single-phase transformer units per generator, *Itaipu*

Three single phase transformers give a 3-phase unit:

Single pahse:
18 kV / 525 kV

a) 825 MVA, 50 Hz (*Paraguay*)

b) 768 MVA, 60 Hz, (*Brazil*)

Source: S. Krauter, Wikipedia

1. 1. History and significance of electric machinery

Power transmission to *Brazil* via AC and DC lines, *Itaipu*, *Parana* river

Furnas AC-DC rectifier: 6000 MW:
500 kV/ 50 Hz from Paraguay generators to DC +/- 500 kV

Back conversion to AC/60 Hz at *Ibiuna* near *Sao Paolo, Brazil*

AC transmission to *Sao Paolo, Brazil*:
6300 MW, 60 Hz, 750 kV, from *Brazil* generators, 891 km

Source: S. Krauter, Wikipedia